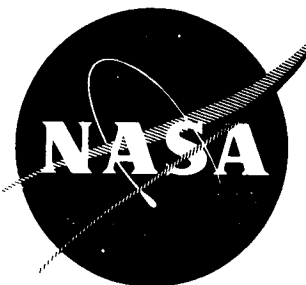


N65-27619
(ACCESSION NUMBER)
174
(PAGES)
(NASA CR OR TMX OR AD NUMBER)

(THRU)
1
(CODE)
03
(CATEGORY)

NASA CR-54415
WAED 65.28E



GPO PRICE \$ _____
OTS PRICE(S) \$ _____
Hard copy (HC) 5.00 .
Microfiche (MF) 1.00

SPACE ELECTRIC POWER SYSTEMS STUDY

D-C TO D-C CONVERTERS FOR NUCLEAR-THERMIONIC ENERGY SOURCES

by

E. F. Swiderski
R. D. Jessee
G. E. Gerecke

prepared for
NATIONAL AERONAUTICS AND SPACE ADMINISTRATION

Contract NAS3-6011



Westinghouse Electric Corporation
AEROSPACE ELECTRICAL DIVISION
LIMA, OHIO

Copies of this report can be obtained from:

National Aeronautics and Space Administration
Office of Scientific and Technical Information
Washington, D. C., 20546
Attn: AFSS-A

NOTICE

This report was prepared as an account of Government-sponsored work. Neither the United States, nor the National Aeronautics and Space Administration (NASA), nor any person acting on behalf of NASA:

- (A) Makes any warranty or representation, expressed or implied, with respect to the accuracy, completeness, or usefulness of the information contained in this report, or that the use of any information, apparatus, method, or process disclosed in this report may not infringe privately-owned rights; or
- (B) Assumes any liabilities with respect to the use of, or for damages resulting from the use of any information, apparatus, method or process disclosed in this report.

As used above, "person acting on behalf of NASA," includes any employe or contractor of NASA, or employe of such contractor, to the extent that such employe or contractor of NASA or employe or such contractor prepares, disseminates, or provides access to, any information pursuant to his employment or contract with NASA, or his employment with such contractor.

CASE FILE COPY

SPACE ELECTRIC POWER SYSTEMS STUDY
D-C TO D-C CONVERTERS FOR NUCLEAR-THERMIONIC ENERGY SOURCES

by

E. F. Swiderski
R. D. Jessee
G. E. Gerecke

prepared for

NATIONAL AERONAUTICS AND SPACE ADMINISTRATION

May 1965

Contract NAS3-6011

Technical Management
NASA Lewis Research Center
Cleveland, Ohio
Solar and Chemical Power Branch
E. A. Koutnik

WESTINGHOUSE ELECTRIC CORPORATION
AEROSPACE ELECTRICAL DIVISION
Box 989
Lima, Ohio 45801

(UNCLASSIFIED)

NASA CR-54415
REPORT NO. WAED 65. 28E

May 1965

SPACE ELECTRIC POWER SYSTEMS STUDY
D-C TO D-C CONVERTERS FOR NUCLEAR-THERMIONIC ENERGY SOURCES

Prepared by:

G. E. Gerecke 5-20-65
G. E. Gerecke
Standard Apparatus Engineering

Approved by:

H. B. James 5/20/65
H. B. James
Supvr. Advanced Program Engineering

R. D. Jessee 5-20-65
R. D. Jessee
Advanced Program Engineering

H. B. Saldin 5.20.65
H. B. Saldin
Mgr. Advanced Program Engineering

E. F. Swiderski 5.20.65
E. F. Swiderski
Advanced Program Engineering

N. W. Bucci 5.20.65
N. W. Bucci
Mgr. Engineering Department

(UNCLASSIFIED)

PREFACE

The authors wish to acknowledge the technical assistance of Messrs. M. A. Geyer and T. M. Heinrich of the Westinghouse Electric Corporation, Lima, Ohio. The authors also wish to acknowledge the technical guidance and direction of Messrs. H. B. James of the Westinghouse Electric Corporation and E. A. Koutnik of the NASA Lewis Research Center.

Space Electric Power Systems Study
D-C to D-C Converters for Nuclear-Thermionic Energy Sources

by

E. F. Swiderski
R. D. Jessee
G. E. Gerecke

Westinghouse Electric Corporation

ABSTRACT

This report presents the results of a study of d-c to d-c converters used in a 3.25 megawatt power system for space ion thruster electric propulsion. A 30-kw converter using silicon controlled rectifiers in the inverter circuit and silicon diodes as rectifiers was compared to a 30-kw converter using vapor tube thyratrons in the inverter circuit and gas tube diodes as rectifiers. The converters operated from a 150 volt nuclear-thermionic source and provided a 5000 volt output. Considering effects of thermal radiators, source weight penalties, nuclear radiation shielding, transmission line conductors and their cooling requirements, the vapor and gas tube switching device converter system weighs less than the power silicon semiconductor converter system. Therefore, the vapor and gas tube converter was selected for further study. Weight, volume, and power losses were determined for 30-kw converters using these devices when operating in 6 groups of 17 converters each. The input voltages were 50 and 100 volts. The output remained at 5000 volts.

TABLE OF CONTENTS

Section	Title	Page
	List of Illustrations	ix
	List of Tables	xiii
	Summary	xv
I	INTRODUCTION	1
II	CONCEPTUAL DESIGN	3
	A. ASSUMPTIONS AND GUIDELINES	5
	B. NUCLEAR-THERMIONIC GENERATOR VOLTAGE-CURRENT RATING	6
	C. ELECTRICAL DESIGN DESCRIPTION	11
	D. MECHANICAL DESIGN DESCRIPTION	15
III	FUNCTIONAL BLOCK ANALYSIS OF TASK A AND TASK B CONVERTERS	19
	A. ELECTRICAL DESIGN	19
	1. Input Filter	19
	2. Inverter Switching Circuit	25
	3. Power Transformers	41
	4. Power Rectifier	48
	5. Output Filter	57
	6. Frequency Reference Oscillator	63
	7. Voltage Regulator	65
	8. Drive Amplifier	72
	9. Overcurrent Protection	76
	B. MECHANICAL DESIGN OF TASK A CONVERTER	80
	1. Functional Block Package Number 1	80
	2. Functional Block Package Number 2	85
	3. Functional Block Package Number 3	88
	4. Converter Data and Summary of Results	91
	C. MECHANICAL DESIGN OF TASK B CONVERTER	97
	1. Functional Block Package Numbers 4-7	97
	D. COMPARISON OF TASK A AND TASK B CONVERTERS.	101

TABLE OF CONTENTS (Cont.)

Section	Title	Page
IV	CONVERTER SYSTEM ANALYSIS OF TASK C AND TASK D ..	109
A.	ELECTRICAL SYSTEM	109
1.	Converter System for Task C	113
2.	Converter System for Task D	115
	Nuclear-Thermionic Source Requirements ...	117
3.	Converter Description	119
B.	MECHANICAL SYSTEM	122
1.	Design of Task C and Task D Converters	122
2.	Functional Block Package Numbers 8-12	125
V	CONCLUSIONS AND RECOMMENDATIONS	131
VI	BIBLIOGRAPHY	133
VII	APPENDIX - COMPUTER PROGRAMING INFORMATION....	135

LIST OF ILLUSTRATIONS

Figure	Title	Page
1	Block Diagram of Electrical Conceptual Design for D-C to D-C Converter, Task A and Task B	4
2	3.25-MW Nuclear-Thermionic Space Powerplant Electrical Characteristics	7
3	Nuclear-Thermionic Generator Electrical Characteristics, Task A	8
4	Nuclear-Thermionic Generator Electrical Characteristics, Task B	10
5	Radiator Specific Weight Vs. Average Coolant Temperatures ..	17
6	Input Filter Power Losses Per 30-KW Converter Vs. Inverter Switching Frequency, Task A	24
7	Inverter Switching Circuit Schematic Diagrams, Task A and Task B	27
8	Vapor Tube Thyatron Parameters In Conventional Bridge Inverter Circuit, Task B	32
9	Inverter Circuit Power Losses Per 30-KW Converter Vs. Inverter Switching Frequency, Task A	38
10	Transformer Relative Weight and Losses Vs. Inverter Switching Frequency	43
11	Transformer Specific Weight and Losses Per KVA Vs. KVA Rating	44
12	Transformer Power Losses Per 30-KW Converter Vs. Inverter Switching Frequency, Task A	47
13	Single-Phase Rectifier Bridge Schematic Circuit, Task A and Task B	49
14	Silicon Diode Rectifier Assembly Power Losses Per 30-KW Converter Vs. Inverter Switching Frequency, Task A	55
15	Output Filter Power Losses Per 30-KW Converter Vs. Inverter Switching Frequency, Task A	62

LIST OF ILLUSTRATIONS (Cont.)

Figure	Title	Page
16	Frequency-Reference Oscillator Schematic Circuit, Task A and Task B	64
17	Voltage Regulator Schematic Circuit, Task A and Task B	67
18	Drive Amplifier Number 1 Schematic Circuit, Task A and Task B	73
19	Overcurrent Protection Schematic Circuit, Task A and Task B .	77
20	Block Diagram of Mechanical Conceptual Design for D-C to D-C Converter, Task A	81
21	Typical Arrangement of Rectifier Assembly, Task A	83
22	Typical Assembly Arrangement of Control Circuit Components, Task A	87
23	Typical Assembly Arrangement of Transformer, Task A	89
24	30-KW Converter Total Weight Vs. Inverter Switching Frequency, Task A	96
25	Block Diagram of Mechanical Conceptual Design for D-C to D-C Converter, Task B	98
26	Electrical Conceptual Design for D-C to D-C Converter System, Task C and Task D	110
27	Total Number of Converters Relative to the Number of Non-regulating Converters Vs. Source Utilization Factor, Task C and Task D	112
28	System Weight in Pounds Per Kilowatt Chargeable to Converters as a Function of Source Utilization Factor, Task C	114
29	System Weight in Pounds Per Kilowatt Chargeable to Converters as a Function of Source Utilization Factor, Task D	116
30	Nuclear-Thermionic Generator Voltage Vs. Utilization Factor, Task C and Task D	118

LIST OF ILLUSTRATIONS (Cont.)

Figure	Title	Page
31	Converter Overcurrent Protection Technique with Current Transformer, Task C and Task D	121
32	Block Diagram of Mechanical Conceptual Design for 30-KW Converter, Task C and Task D	124
33	Block Diagram of Mechanical Conceptual Design for 510-KW Converter Power Channel, Task C and Task D	126
34	Converter Schematic Diagram, Task B	136
35	Partial Analog of Converter, Task B	151
36	Partial Analog of Converter, Task B	153
37	Analog of Clock Pulses, Task B	155
38	Logic for Thyratrons, Task B	157

LIST OF TABLES

Table	Title	Page
1	Summary of Weight, Volume, and Power Losses for 30-KW Converters, Tasks A, B, C, and D	xvii
2	Preliminary Capacitor Characteristics, Task A	21
3	Input Filter Data for 30-KW Converter and 3.25-MW Converter System, Task A and Task B	23
4	Preliminary Silicon Controlled Rectifier Characteristics, Task A	28
5	Preliminary Vapor Tube Thyatron Characteristics, Task B ...	29
6	Preliminary Gas Tube Diode Characteristics, Task B	30
7	Inverter Circuit Data for 30-KW Converter and 3.25-MW Converter System, Task A	36
8	Inverter Circuit Data for 30-KW Converter and 3.25-MW Converter System, Task B	37
9	Power Transformer Data for 30-KW Converter and 3.25-MW Converter System, Task A	45
10	Power Transformer Data for 30-KW Converter and 3.25-MW Converter System, Task B	46
11	Preliminary Gas Tube Diode Characteristics, Task B	52
12	Silicon Diode Rectifier Assembly Data for 30-KW Converter and 3.25-MW Converter System, Task A	53
13	Gas Tube Diode Rectifier Assembly Data for 30-KW Converter and 3.25-MW Converter System, Task B	54
14	Output Filter Data for 30-KW Converter and 3.25-MW Converter System, Task A	59
15	Output Filter Data for 30-KW Converter and 3.25-MW Converter System, Task B	60
16	Frequency-Reference Oscillator Power Losses for 30-KW Converter and 3.25-MW Converter System, Task A and Task B.	66

LIST OF TABLES (Cont.)

Table	Title	Page
17	Voltage Regulator Power Losses for 30-KW Converter and 3.25-MW Converter System, Task A and Task B	71
18	Drive Amplifier Power Losses for 30-KW Converter and 3.25-MW Converter System, Task A and Task B	75
19	Overcurrent Protection Circuit Power Losses for 30-KW Converter and 3.25-MW Converter System, Task A and Task B ...	79
20	Weight Data for 30-KW Converter and 3.25-MW Converter System, Task A	92
21	Volume Data for 30-KW Converter and 3.25-MW Converter System, Task A	93
22	Power Loss Data for 30-KW Converter and 3.25-MW Converter System, Task A	94
23	Weights with Source and Radiator Penalties for 30-KW Converter and 3.25-MW Converter System, Task A	95
24	Weights, Volumes, and Power Losses for 30-KW Converter and 3.25-MW Converter System, Task B	102
25	Comparative Data for 30-KW Converter and 3.25-MW Converter System, Task A and Task B	103
26	Converter Component Radiation Tolerance, Task A and Task B.	105
27	Weight Comparison for 3.25-MW Converter System, Task A and Task B	107
28	Possible Converter System Combinations for Task C	115
29	Possible Converter System Combinations for Task D	117
30	Converter System Electrical Parameters, Task C and Task D..	123
31	Weight, Volume, and Loss Data for 510-KW Converter Power Channel and 3.25-MW Converter System, Task C	129
32	Weight, Volume, and Loss Data for 510-KW Converter Power Channel and 3.25-MW Converter System, Task D	130

Space Electric Power Systems Study
D-C to D-C Converters for Nuclear-Thermionic Energy Sources

by

E. F. Swiderski
R. D. Jessee
G. E. Gerecke

Westinghouse Electric Corporation

SUMMARY

This report presents conceptual data for several d-c to d-c converters. The converters studied operate from a 3.25-mw nuclear-thermionic source at nominal input voltages of 50, 100, and 150 volts and provide a 5000 volt output. Task A and Task B considered a source-converter system which consists of 102 electrically isolated channels with a 30 kilowatt capacity per channel. The input voltage was 150 volts. The converters for Task C and Task D are grouped into 6 electrically isolated power channels with seventeen 30-kw converters per channel. The Task C converters operate with a 50 volt input while the Task D converters operate from a 100 volt input. The converters of Task A used silicon controlled rectifiers in the inverter circuit and silicon diodes as rectifiers. The converters for Tasks B, C, and D used vapor tube thyratrons in the inverter circuit and vapor and gas tube diodes as rectifiers. These devices have an envelope capability of 600 to 800°C.

The weight, volume, and power losses of the d-c to d-c converters studied are summarized in Table 1. The tabulated values are based on a 30-kw converter rating.

The converter weight is shown with and without source and thermal radiator penalties. Specific weight is provided under the same conditions. Weight information is presented for Task A and Task B only when the effects of nuclear radiation shielding, transmission line conductors, and their cooling requirements are considered. The Task B converter system, using vapor tube thyratrons and gas tube diodes, weighs less than the Task A semiconductor converter system.

In Task C and Task D a single output filter was used for each group of seventeen 30-kw converters. An input filter was not necessary for these converters. The values in Table 1 represent 1/17 that used for the 17 converter power channel.

The power losses, efficiency, thermal radiator, and source penalty for the Task A converters are based on an inverter switching frequency of 2300 cycles per second. The same data for the Task B converters are based on an inverter frequency of 200 cycles per second.

TABLE 1

**SUMMARY OF WEIGHT, VOLUME, AND POWER LOSSES
FOR 30-KW CONVERTERS, TASKS A, B, C, AND D**

	CONVERTERS			
	Task A	Task B	Task C	Task D
Rating of Single Converter (kw)	30	30	30	30
Nominal Converter Input Voltage (volts)	150	150	50	100
Power Switching Devices	Silicon Semi-conductors		600 to 800°C Vapor & Gas Tubes	
Number of Converters Per Channel	1	1	17	17
Number of Channels Per 3.25-MW System	102	102	6	6
Volume (ft. ³)	2.6	11.4	35.4	14.3
Power Losses (watts)	2096	4741	8933	6050
Packaged Converter Wt. (lbs.)*	175.3	863.8	2816	1124
Packaged Converter Wt. and Penalties (lbs.)+	218.3	1001	2923	1198
Source Over Capacity Penalty (lbs.)	0	75	200	200
Total Weight (lbs.)	218.3	1076	3123	1398
Converter System Weight (lbs.)#	1434	1187	--	--
Specific Weight, Converter (lbs./kw)	5.84	28.79	93.8	37.5
Specific Wt., Converter Wt. & Penalties (lbs./kw)	7.27	35.86	104	46.6
Specific Wt., Converter System (lbs./kw)	47.8	39.6	--	--
Converter Efficiency (%)	93.4	86.4	77.3	83.2

*Converter weight. Includes electrical components, structure, and cooling system.

+Converter weight plus thermal radiator and source weight penalties.

#System weight. Includes converter, thermal radiator, source weight, source over capacity, nuclear shield, transmission line conductors, and their cooling requirements.

SECTION I
INTRODUCTION

INTRODUCTION

Previous studies have considered both dynamic and static conditioning equipment systems to provide power for electric ion propulsion systems. Initial work on NASA Contract NAS5-1234 was concerned with parametric and conceptual data for a-c to d-c power conditioning equipment using a nuclear reactor and a turbo-generator as the electric energy source. The data on these studies are reported in Space Electric Power Systems Study, Volumes 1 through 4. The work on Amendment 6 of NAS5-1234 presented in Space Electric Power Systems Study, Volume 5, considers parametric data for static d-c to d-c converters using a nuclear-thermionic energy supply as the power source. All of the work on Contract NAS5-1234 was performed by the Westinghouse Electric Corporation, Aerospace Electrical Division, Lima, Ohio.

The effort on this contract is a continuation of the work performed on Amendment 6 of NAS5-1234 and is to present the conceptual data on static d-c to d-c converters for electric ion engines. Technical work was performed during the period of June 1964 to April 1965. Where applicable, this report uses the Volume 5 information directly or provides adequate reference. Conceptual data of size, weight, heat losses, efficiency and coolant temperatures are determined in this report for the functional blocks that make up the d-c to d-c converters.

The converters analyzed and the technical direction for this study are as defined in Contract NAS3-6011. The work statement, as presented in the contract for the converter systems to be investigated, is as follows:

Task A

A 3.25 megawatt (mw) system with 150 volt d-c input, 5000 volt d-c output, utilizing silicon controlled rectifiers for inverter switching and silicon diodes as rectifiers. The system shall consist of 102 electrically isolated channels with a 30 kilowatt (kw) capacity per channel.

Task B

A 3.25-mw system with 150 volt d-c input, 5000 volt d-c output, using 250 ampere, 200 volt high temperature vapor tubes as inverter switches and high temperature gas tube diodes as rectifiers. The system shall consist of 102 electrically isolated channels with 30-kw capacity per channel. It is to be expected that thermionic elements for Task A and Task B shall be divided into 102 groups, each with sufficient capacity to produce 30 kilowatts.

Task C

A 3.25-mw system with 50 volt d-c input, 5000 volt d-c output consisting of a number of electrically isolated channels. The selection of the number of channels and choice between tubes or semiconductors shall be based on the study results of Task A and Task B above and the resultant data produced under NASA Contract NAS5-1234.

Task D

A 3.25-mw system with 100 volt d-c input, 5000 volt d-c output composed of a number of electrically isolated channels. The selection of the number of channels and choice between tubes or semiconductors shall be based on the study results of Task A and Task B above and the resultant data compiled under NASA Contract NAS5-1234. The selection of system configuration for Task C and Task D shall be made by NASA. It is planned that thermionic elements shall be divided into groups with sufficient capacity to match the number of channels selected by NASA.

The following sections of this report present the converter data for the above tasks.

SECTION II
CONCEPTUAL DESIGN

CONCEPTUAL DESIGN

Fundamentally, the conversion of relatively low d-c voltages to higher magnitudes involves power switching circuits which alternately interrupt the flow of direct current. These circuits provide a-c square-wave or quasi-square wave voltages which are stepped up in magnitude by transformers and then converted to direct voltage by output rectifiers. To complete a practical d-c to d-c power converter, a frequency reference oscillator, drive amplifier, voltage regulator, overcurrent protection circuit, and filters must be provided.

The converters studied in this program are similar in concept although they differ in detail. Each converter includes the primary power circuit and secondary control circuits. A block diagram of the electrical conceptual converter design for Task A and Task B is shown in Figure 1.

The block diagram used for the converters of Task C and Task D is presented in another part of this report.

The assumptions and guidelines used to direct the conceptual study efforts of this program are presented in this section. This is followed by a discussion on the nuclear-thermionic source characteristics and the converter electrical and mechanical design descriptions. Additional pertinent assumptions and guidelines are presented in the mechanical design discussion of this section of the report.

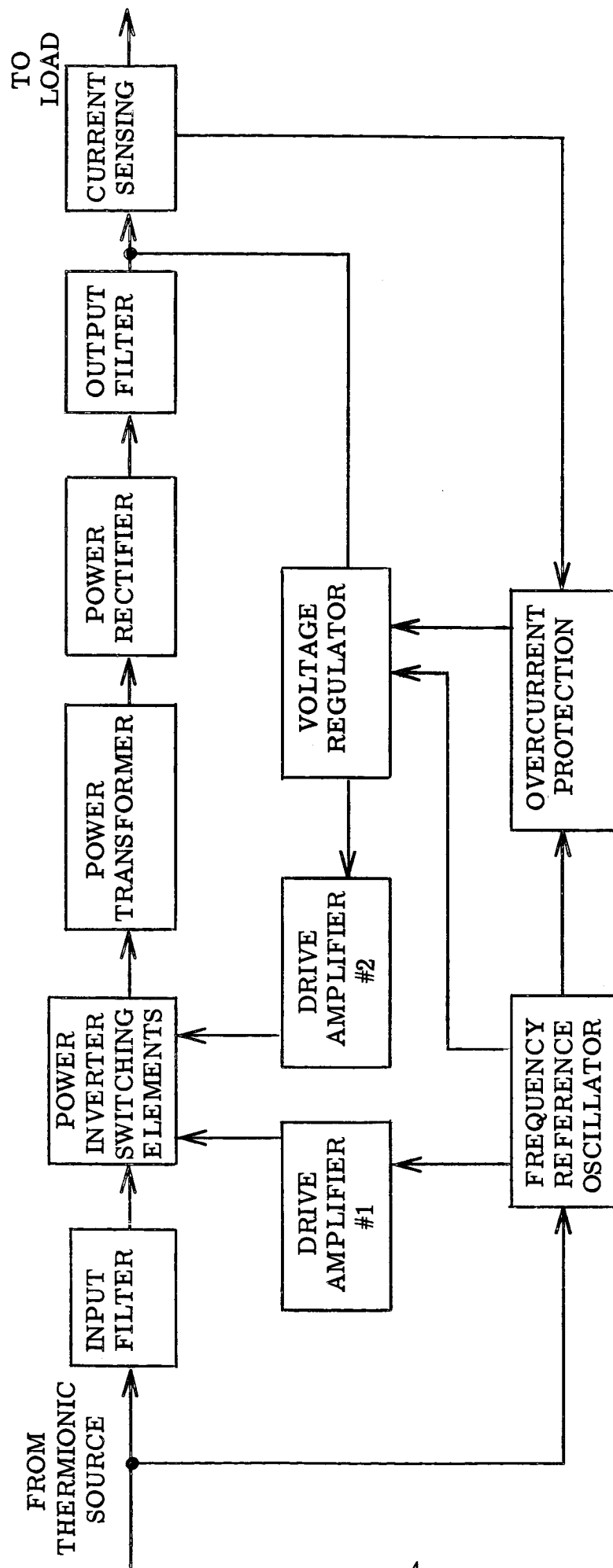


FIGURE 1

Block Diagram of Electrical Conceptual Design For D-C To D-C Converter, Task A and Task B

A. ASSUMPTIONS AND GUIDELINES

1. The study presents only conceptual data for the functional blocks which make up the d-c to d-c converters. The report does not present detailed design information or outline drawings. The effects of heat dissipative radiator and electric power source weight penalties on converter system weight are considered.
2. The use of single-phase inverter circuits is based on the study results reported in Space Electric Power Systems Study, Volume 5, under Contract NAS5-1234, Amendment 6.
3. Selection of the inverter switching frequency for Task A is based on a minimum-weight converter system. The inverter switching frequency for Task B is chosen so as not to exceed the vapor-tube thyratron voltage rating of 200 volts in the forward direction. The inverter frequency for Task C and Task D will be the frequency used with the semiconductor switching devices of Task A or the frequency used with the tube devices of Task B.
4. Efficiency, size, weight, power losses, and coolant temperature are presented for the functional blocks of the d-c to d-c converters.
5. The d-c to d-c converter load is considered a constant-resistance ion engine high voltage circuit. Load voltage is held at 5,000 volts d-c $\pm 5\%$ with a maximum voltage ripple of 4%. Steady-state output current is limited to 1.25 the full-load value during short circuit conditions. No specification is established for no-load output voltage.
6. The interconnecting conductors between the converter functional blocks are not considered.
7. Fluctuation of source voltage due to sputtering in the thermionic diodes is not considered. The input filter is based only on the requirements of the inverter circuits.
8. The conceptual data are based on engineering estimates of the characteristics of electric components and materials available by 1968. The availability of components and materials is estimated on normal industry progress or government funded programs and does not recognize crash development programs.
9. Effects of nuclear radiation have been considered only to the extent of comparing shield weights between the converters of

Task A and Task B. The amount of nuclear shielding required for the converters of Task C and Task D is not a part of this study.

B. NUCLEAR-THERMIONIC GENERATOR VOLTAGE-CURRENT RATING

The basic generator volt-ampere characteristic, used in this study, is shown as the 100% thermal power curve in Figure 2. It is assumed in this study that the source volt-ampere characteristic varies by $\pm 10\%$ from the nominal. The "limit" curves are assumed to have a corresponding 10% change in current for a 10% change in voltage from all points on the base curve. It is further assumed that the source impedance is purely resistive.

It is logical to select an operating point which makes maximum use of the nuclear-thermionic source capability. Thus, when the source output volt-ampere characteristic is at the lower limit, the load should draw the maximum available power from the source. A non-dissipative voltage regulating technique is used in this study as discussed in Section II C. With this technique, the power demand on the source will remain constant even though the source capability increases. Figure 3 illustrates the selection of the operating point. Curve V_2 is the normal source-voltage characteristic as a function of load current. Curve V_3 is the high limit and Curve V_1 the low limit of the nuclear-thermionic output. The curves are plotted in per-unit quantities where the normal open-circuit voltage is V_0 and the normal short circuit current is I_S . Curve P_1 is the output power of the source during low-limit operation, i. e., when the source output voltage is V_1 .

Choice of the operating point on V_1 determines the values V_0 and I_S required for the system. Assumption that P_m is the maximum power required by the system establishes point (1) on the lower-limit volt-ampere curve. Further, assuming non-dissipative voltage control, the source output voltage and current for full load is defined by curve V_4 , a volt-ampere curve for constant power. At the normal operating point (2), the average source output voltage is $V_2 = 0.75 V_0$.

Task A

The converter input voltage for Task A is specified as 150 volts d-c. Thus, $V_2 = 0.75 V_0 = 150$ volts and $V_0 = 200$ volts. The current at point (2) is $0.35 I_S = P_m/150$, and $I_S = 0.019 P_m$ amperes where P_m is the total power in watts delivered by the source.

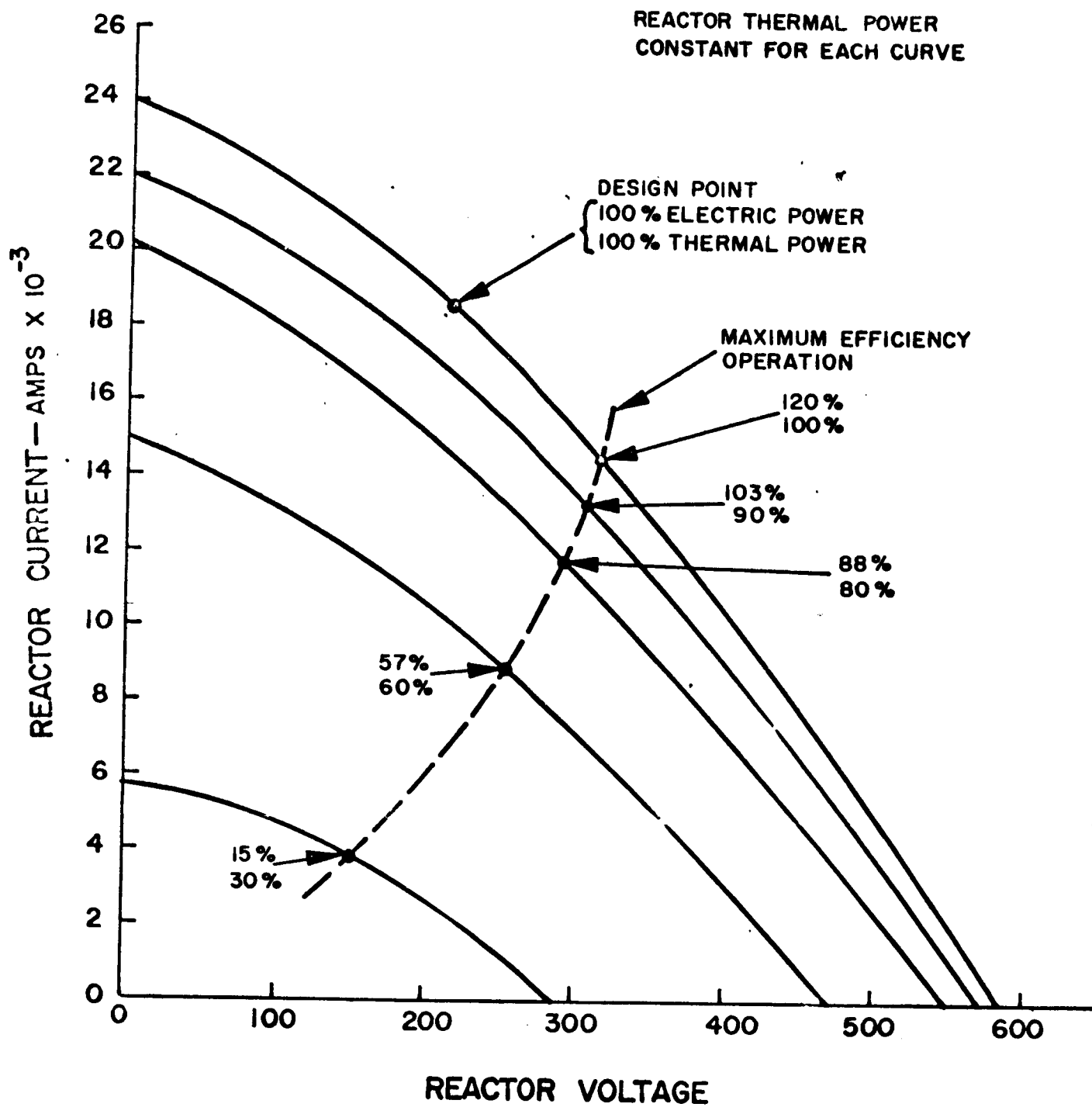


FIGURE 2

3. 25-MW Nuclear-Thermionic Space Powerplant
Electrical Characteristics

Pratt &
Whitney
Aircraft

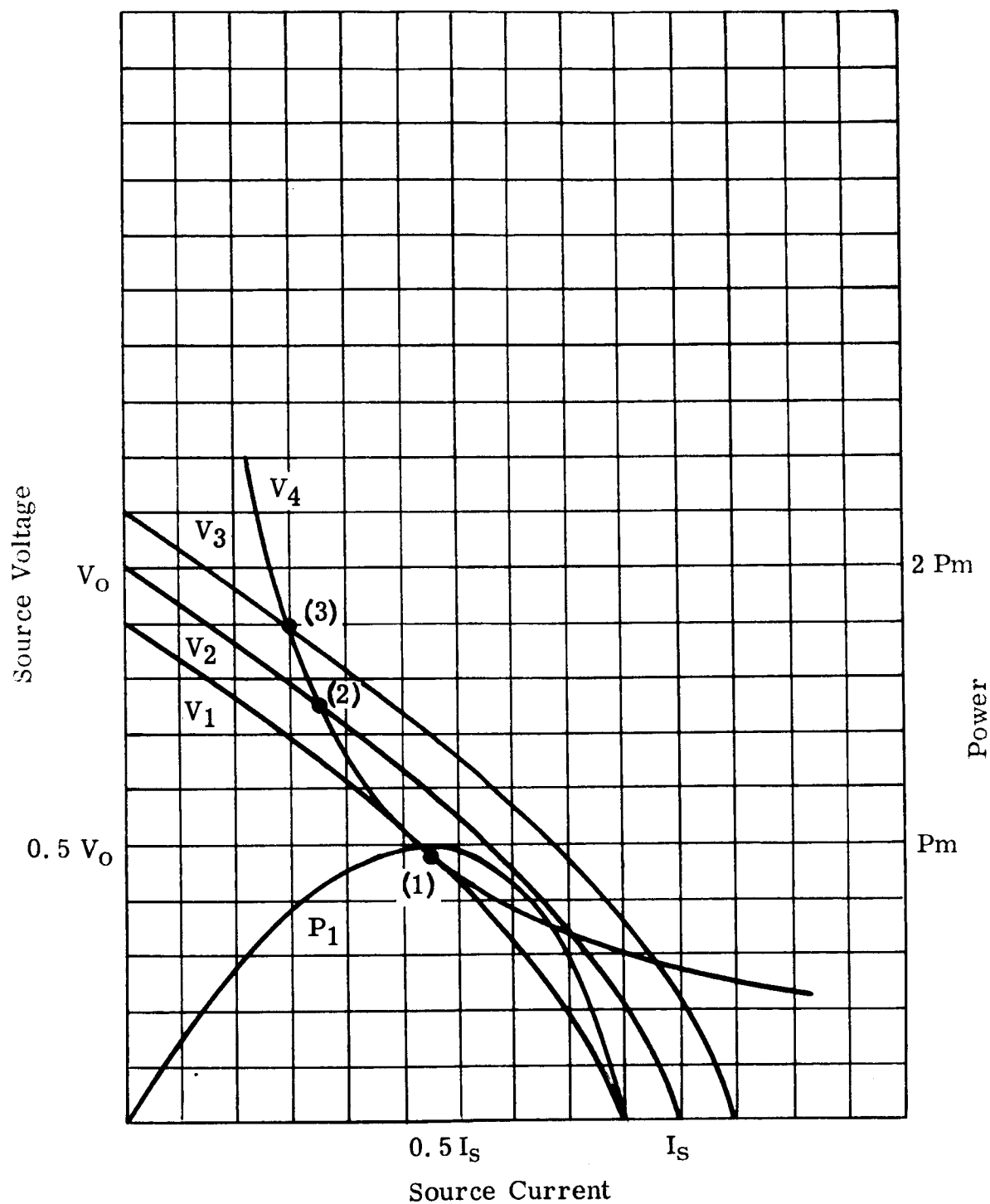


FIGURE 3

Nuclear-Thermionic Generator
Electrical Characteristics, Task A

If the converter load is removed, the source voltage rises to its open circuit value. With the use of overcurrent load limiting, the source voltage will also rise to its open circuit value on short circuit. This value is $1.1 V_O$ when the source operates on the high limit volt-ampere curve. For Task A the upper limit of the open circuit voltage is 220 volts. The average converter input voltage at full load may vary from 98 to 180 volts, represented by points (1) and (3) respectively as shown in Figure 3.

Task B

Selection of the voltage and current rating of the thermionic source required for Task B differs in one important respect from that of Task A. The controlled rectifier tubes (thyratrons) used in the inverter for Task B are limited in forward voltage rating to 200 volts. Therefore, the source parameters of Task A cannot be used for Task B, since the maximum source open circuit voltage for Task A is 220 volts.

To make maximum utilization of the thermionic source (as in Task A), the maximum open circuit voltage for Task B is $1.1 V_O = 200$ volts and $V_O = 182$ volts. From Figure 3 the normal operating source voltage at point (2) is $0.75 V_O$. Therefore, for Task B, $0.75 (182) = 137$ volts would give the nominal operating point, and the minimum voltage point would be defined as $0.49 V_O = 89.5$ volts. The normal operating voltage specified for Task B, however, is 150 volts. Figure 4 shows the parameters required to meet the specified conditions. Maximum voltage is $1.1 V_O = 200$ volts and $V_O = 182$ volts as before. Since the operating voltage at point (2) is $V_2 = 150$ volts, $V_2/150 = 1.1 V_O/200$ and $V_2 = 0.825 V_O$. When $V_2 = 0.825 V_O$, $I = 0.26 I_S$ and load power = $0.214 V_O I_S$. Plotting V_4 vs. I for constant power, where $V_4 I = 0.214 V_O I_S$ defines points (1) and (3) on the "limit" curves. The voltage to the converter with full-load output varies from $0.68 V_O$ to $0.95 V_O$ or 124 to 173 volts. This is a smaller voltage variation than realized in Task A.

It should be noted that the power output from the source when operating at point (1) of Figure 4 is $P_1 = 0.8 P_M$. The source, therefore, has a capacity of 1.25 that required by the load under the worst assumed conditions. This 25% penalty in required thermionic source capacity is the result of the voltage limitation on the converter controlled rectifier tubes and the specified normal operating voltage. This penalty could be eliminated by operating at a 137 volt nominal point rather than at 150 volts.

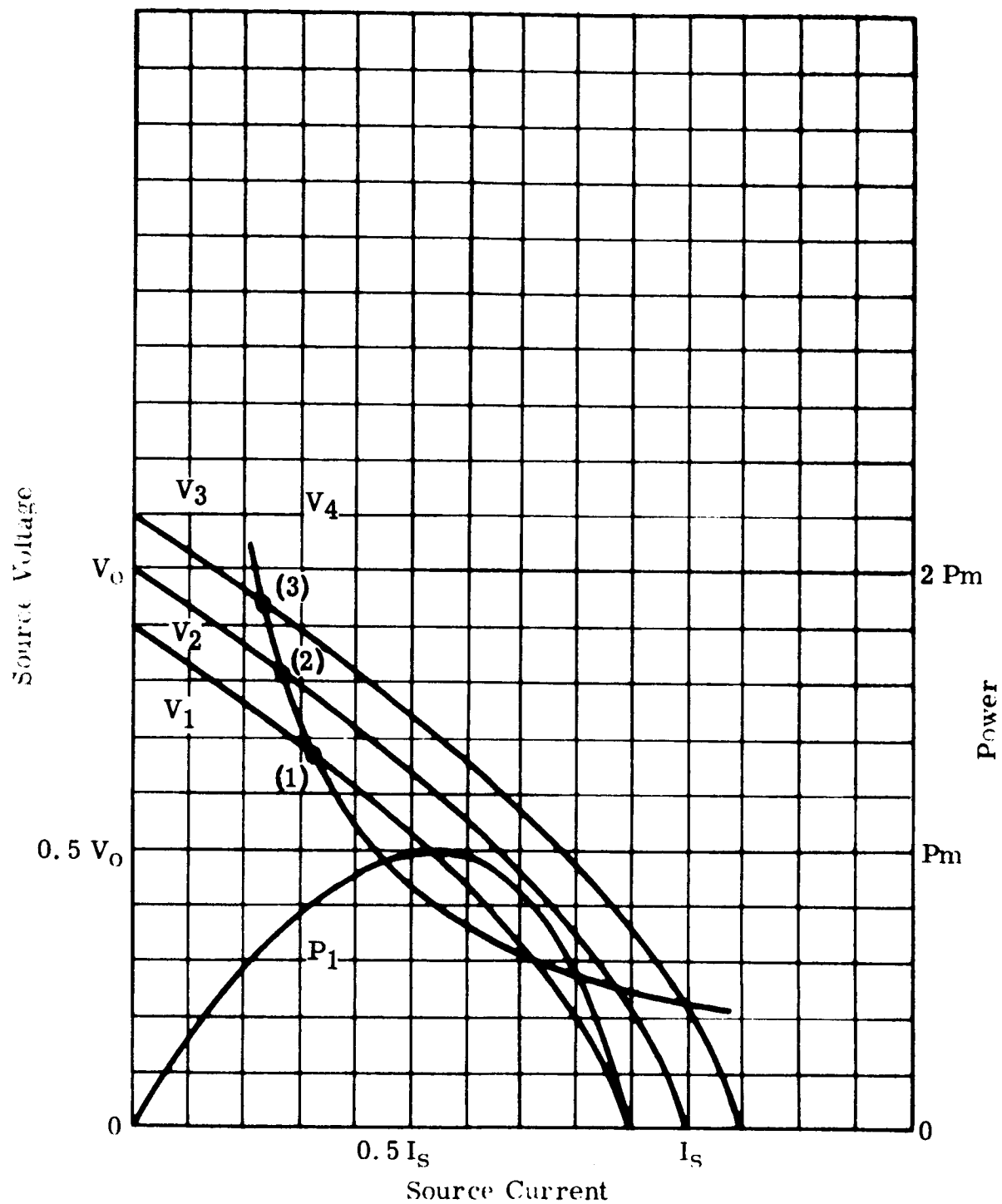


FIGURE 4

Nuclear-Thermionic Generator
Electrical Characteristics, Task B

C. ELECTRICAL DESIGN DESCRIPTION

The following paragraphs describe in a general way the functions of each block represented in Figure 1. The power-circuit functions of the converters are described first, followed by the functional description of the control circuits. The circuit operation to perform the required functions is reserved for the functional analysis part of this report.

Input Filter

The function of the input filter is to supply energy during the initial part of the inverter commutating interval and absorb energy during the latter part of the commutating interval, maintaining a relatively smooth d-c voltage on the input bus. This filter also aids in reducing any voltage surges caused by sputtering in the thermionic source. The input filter is a capacitor and is physically located at the input to the inverter.

Inverter

The function of the inverter is to change the d-c power of the nuclear-thermionic source to a-c power, which is necessary to provide means of stepping up the voltage level through the use of transformers.

D-C to a-c inversion can be accomplished by any of several known single-phase or polyphase circuits. The choice of the best circuit depends on the specific application. For spacecraft propulsion applications, the best circuit results in minimum propulsion system weight. This does not necessarily mean that the lightest inverter is best since other system equipment parameters or other converter components are affected by the inverter circuit used.

The inverter circuit selected for Task A of this study is the single-phase center-tap using, according to contract requirements, silicon controlled rectifiers. Two modules of the center-tapped circuit are used to make up one inverter to permit phase shift voltage control. In the earlier work performed on Contract NAS5-1234, Amendment 6, it was determined that the single-phase, center-tap controlled rectifier circuit was most desirable. The selection of the best circuit considered the electric component weights of the power and control circuits and the weight influence by the nuclear-thermionic source and thermal radiator because of the component power losses.

To make use of the 200 volt vapor-tube thyatron, at a 150 volt converter input, the inverter circuit selected for study for Task B is the single-phase pulse-width modulated bridge.

Power Transformer

There are several single-phase and polyphase transformer designs which can be used in d-c to d-c converter systems. The selection of the single-phase transformer for use in the conceptual study is dictated by the choice of the single-phase inverter circuit.

The function of the power transformer is to step up the voltage level of the a-c square waves or quasi-square waves produced by the inverter to a level which provides the desired direct output voltage after rectification.

The basic transformer configuration consists of a single-phase core with single primary and secondary windings.

Power Rectifier Assembly

The function of the rectifier assembly is to convert the a-c square wave or quasi-square wave voltage of the power transformer secondaries into the desired direct output bus voltage. As in the case of the power transformer, the selection of single-phase rectification is dictated by the choice of the single-phase inverter circuit. The possible circuits for this application are the single-phase, full-wave bridge rectifier and the single-phase, center-tapped, full-wave rectifier. Both circuits require the same number of diodes when the inverse voltage is considered. The full-wave bridge rectifier, however, uses a smaller power transformer for the same d-c power delivered to the load. This circuit is, therefore, selected for conceptual study.

Output Filter

The function of the output filter is to reduce the ripple voltage on the d-c output bus to a value compatible with the load requirements. The filtering requirement is dependent on the inverter circuit, its switching frequency, and the type of voltage regulation employed. The conceptual study is based on a conventional low-pass, L-C filter that maintains the output ripple voltage below 4 percent rms for resistive loads.

Frequency-Reference Oscillator and Drive Amplifier

The frequency-reference oscillator generates a square-wave voltage that is amplified by the drive amplifier. It, therefore, determines the operating frequency of the power inverter circuit. The frequency-reference consists of a self-starting transistor oscillator the frequency of which is proportional to its input voltage. Since the input voltage comes from a tap on the main d-c bus, the oscillator generates a frequency proportional to this bus voltage. This variable frequency is desirable because it prevents saturation of the inverter power transformers if the input bus voltage rises.

The drive amplifier consists of a semiconductor switching circuit that provides an a-c square wave at the correct voltage and current to gate the inverter controlled rectifiers (solid state and vapor tube). Two separate drive amplifiers are used per converter. The output voltage wave of one of the amplifiers is in phase with the frequency reference oscillator whereas the second drive amplifier voltage wave is phase delayed by the voltage regulator to provide converter output voltage control.

Voltage Regulation

A voltage regulator is required to maintain the converter output voltage within $\pm 5\%$ of its nominal value. The regulator will function to correct for converter input voltage variations as caused by changes in the nuclear-thermionic source. It has been assumed that the variation in the source can cause open circuit voltage changes of $\pm 10\%$.

In the work performed on Contract NAS5-1234, Amendment 6, voltage regulation of the d-c to d-c converters was achieved by turning off an appropriate number of inverter power stages when the output voltage started to rise. Each stage that was turned off subtracted from the output an increment of voltage approximately equal to the amount it formerly added. Thus, voltage regulation was similar to the tap-changing technique used on electric utility systems. The method of interconnection made it possible to turn off an inverter stage by removing its drive signal. The single converter studied had a power output capacity of 500 to 5000 kilowatts requiring the use of a number of inverter stages. The smallest number of inverter stages used was 24 of which a minimum of 6 were required as regulating types. In this study, requiring an investigation into 30-kilowatt converters, the approach as presented above was not practical for Tasks A and B.

Therefore, other techniques as possible approaches to voltage regulation were considered as follows.

The nature of the power source lends itself to load voltage control by addition of parasitic load directly to the source so as to maintain a total load with a nearly constant generator output voltage. Such a system would operate normally on the short circuit side of the maximum power point of the nuclear-thermionic source volt-ampere characteristic. Control would require a voltage sensing device to signal the addition or removal of parasitic load.

A second method of output voltage control might employ changing the transformer turns-ratio of the inverter stage of the power converter. The technique of voltage control by tap changing as considered for this study is different in detail from that used for the converters on the NAS5-1234, Amendment 6, contract and would be feasible for the 30-kilowatt rated

units of Tasks A and B. This method would require a number of low-power static switching devices operating in response to an output-voltage sensor.

A third method of voltage regulation would provide continuous rather than step voltage control. Here the voltage is controlled by the firing angle of the controlled rectifiers in the inverter. The result is a series of pulses which are filtered to give the desired output level at the given voltage ripple requirement of 4%. This technique of voltage control is identified as phase-shift or pulse-width voltage regulation.

Although pulse-width voltage control requires an output filter, whereas parasitic load control and tap changing do not, certain advantages make it preferable to use pulse-width regulation for this application. From information available in the current literature¹ a "soft start" is desired in applying the ionizer and accelerator voltages to the electric engine load. With pulse-width control, voltage may be applied gradually to the load at the desired rate. It is also desirable that short-circuit current be limited to slightly more than normal full-load current. Steady-state current limiting can be easily affected by controlling the pulse-width in response to a current signal. Pulse-width voltage control was, therefore, selected for the converters of this study.

Overcurrent Protection

The function of the overcurrent protection circuit is to protect the d-c to d-c converter and the electric engine load from damage if load-bus or engine faults occur.

For a minimum weight system, it is necessary that the converter be required to carry a minimum of overload current. The weight of inverter commutating capacitors increases rapidly with increasing overload capability. The means of current sensing and protection described below minimizes both the magnitude and time duration of overload currents.

Overcurrent protection is conveniently incorporated into the pulse-width voltage control of the inverter. The converter load current is sensed through a saturable reactor transducer. A voltage signal produced in response to the load current, is normally too small to have any effect on the voltage regulator. However, should the load current reach an assumed 1.25 per unit, the current signal will override the voltage sensing signal.

¹ Kotnik, J. T. and Sater, B. L., "Power-Conditioning Requirements for Ion Rockets," IEEE Transaction on Aerospace, Vol. 2, No. 2, April 1964, p. 496-504.

This override causes the voltage regulator to reduce the inverter controlled rectifier conduction angle and thus prevents further rise in the steady-state load current. At the same time a signal is applied to the generator contactor trip circuit interrupting the power to the converter.

D. MECHANICAL DESIGN DESCRIPTION

The electrical components of the control circuits for the converters of this study are physically small and lightweight. In packaging these components and the relatively larger size components of the power circuit, the percentage of weight required for structure (for packaged weights below 30 to 40 pounds) increases rapidly with decreasing total weight. To reduce converter structural weight, the packaging philosophy used in this study is to group the individual converter functional circuits into common packages. The choice of grouping is dictated by the maximum allowable temperature for each functional block. Those having the same coolant temperature share the same coolant circuit.

The converter electrical components are mounted to cold plates or structure as described in greater detail in the mechanical functional block section of this report. Eutectic NaK coolant is confined in conduits which become integral parts of the cold plates or structure. The coolant conduits and structure are of beryllium at temperatures below 200°C to achieve low weight with the required resistance to liquid metal corrosion. At temperatures above 200°C, columbium is used to provide this corrosion resistance at the required structural strength.

The following design criteria are assumed for the electrical functional blocks of this study. Additional criteria peculiar to the individual converter circuits are included in the mechanical functional block section of this report.

1. The coolant is assumed to be eutectic NaK, which has a specific heat of 0.210 Btu/lb-°F, and a density of 0.0306 lb/in.³. Convection temperature drop is assumed to be 1°C.
2. Beryllium oxide insulation has the following characteristics.

Dielectric Strength	300 volts/mil
Density	0.105 lb/in. ³
Thermal Conductivity	100 Btu/hr-ft-°F at 100°C
Thermal Expansion	3.2 x 10 ⁻⁶ in/in. °F from 0 to 200°C
	5.0 x 10 ⁻⁶ in/in. °F from 400 to 600°C

3. Beryllium for use in coolant tubes and cold plate has the following characteristics.

Density	0.067 lb/in. ³
Thermal Conductivity	87 Btu/hr-ft-°F
Thermal Expansion	6.4×10^{-6} in./in. °F

4. Columbium for use in coolant tubes and cold plate has the following characteristics.

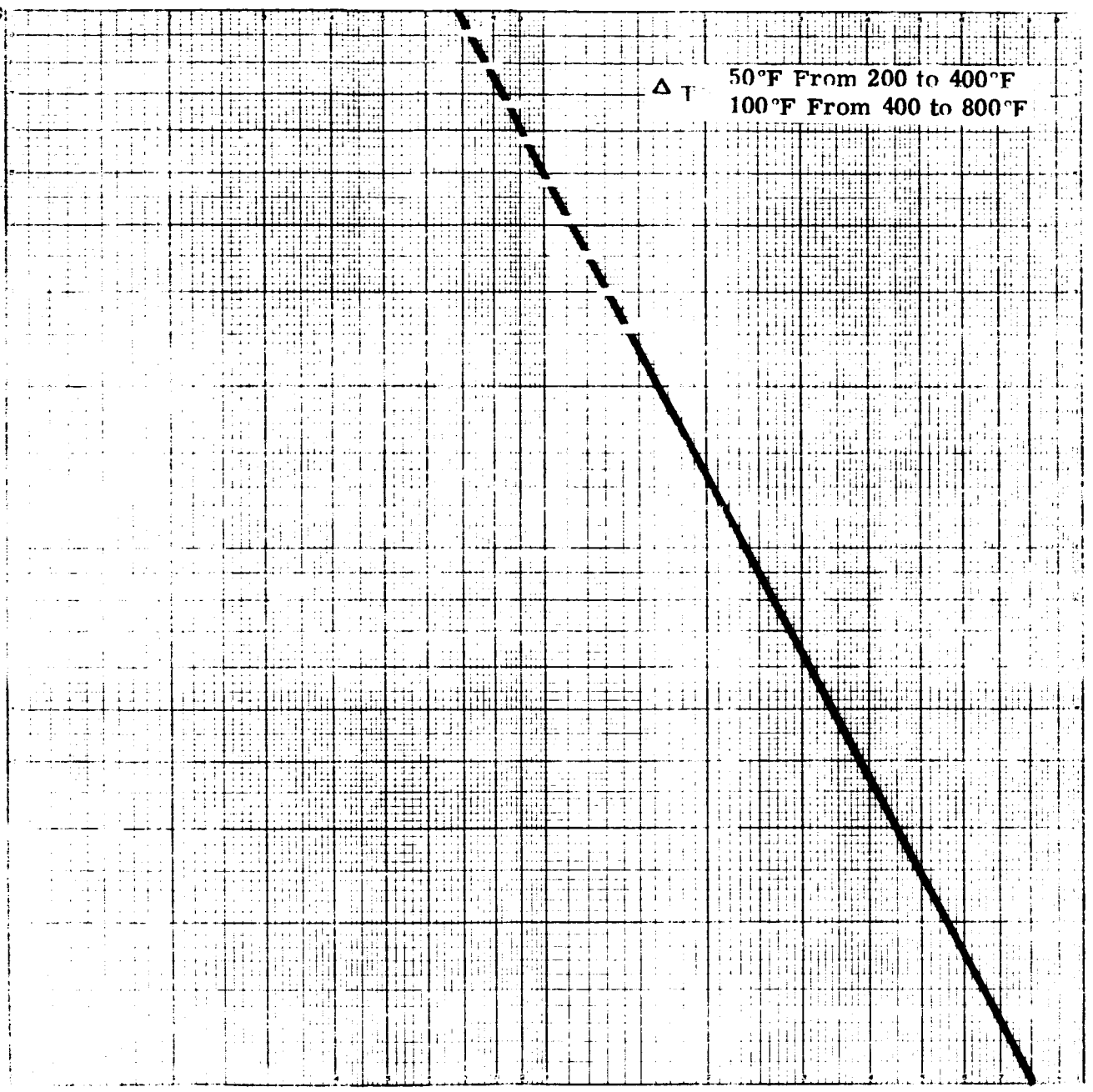
Density	0.310 lb/in. ³
Thermal Conductivity	31.5 Btu/hr-ft-°F
Thermal Expansion	3.82×10^{-6} in./in. °F

5. Adhesive bonding is 0.002 inches thick, with a thermal conductivity of 0.227 Btu/hr-ft-°F.
6. Minimum achievable thermal resistance between two surfaces not bonded together is 0.2°C/watt in a space environment.
7. Conductor weight is assumed to be 5% of the functional block weight for each block.
8. Conductor losses within the functional blocks are not considered.
9. Source weight penalty is assumed to be 10 pounds per kilowatt of loss.
10. The radiator weight penalties are determined from the curve of Figure 5, reproduced from Space Electric Power Systems Study, Volume 5, Contract NAS5-1234, Amendment 6.

The curve is plotted on log-log paper to enable linear extrapolation to lower temperatures.

Radiator Specific Weight - Pounds Per Gallon

100



10

100

1000

Average Coolant Temperature - °F

FIGURE 5

Radiator Specific Weight Vs.
Average Coolant Temperatures

SECTION III

**FUNCTIONAL BLOCK ANALYSIS OF TASK A AND
TASK B CONVERTERS**

FUNCTIONAL BLOCK ANALYSIS OF TASK A AND TASK B CONVERTERS

This section of the report is separated into two parts, the first presenting the converter electrical considerations with respect to circuit design and the second the mechanical engineering aspects of the program regarding packaging and cooling of the converter electrical components.

Reporting the results of the electrical part of the study for the converters of Task A and Task B is on the basis of the functional circuit. Therefore, the requirements for both converters are presented under the individual functional blocks which make up the converters.

On the other hand, the results of the mechanical engineering study have been reported according to task. Therefore, weight, volume, and cooling information for the converter of Task A is separate from similar information for the converter of Task B. Comparison of the conceptual data of the Task A and Task B converters determines the selection of the converter circuit configuration and electrical switching components to be used in Task C and Task D.

The study of the converter functional blocks consists of a description, design criteria, conceptual data, discussion of problem areas, data analysis, and conclusions and recommendations as appropriate and applicable. This information is in separate reports for each functional block, thus allowing each functional circuit of the converter to be examined independently in the manner that the study was performed.

The tabulation of data in the electrical design section is slightly more detailed for the power circuits than for the control circuits since they make up the largest percentage of converter component weight and losses. Evaluation of electrical efficiency has been limited to the power circuit functional blocks only.

Some of the converter conceptual data presented are based on designs using materials or components that require development before practical equipment can be realized. The application of these materials or components is discussed in the appropriate functional block reports.

A. ELECTRICAL DESIGN

1. Input Filter

Inverters utilizing controlled rectifiers (silicon, vapor-tube, etc.) require turn-off circuits employing energy storage. The switching

action demands an energy pulse from the source which is stored in the commutating components and subsequently returned to the source. If the source impedance is negligible, no problem arises from this energy pulsation. It is assumed, however, that the thermionic source has the characteristic of a rectifier so that energy cannot be returned to it. In this study where d-c to d-c converters supplying power to electric ion engines constitute the only load on the source, provision must be made to store the energy pulses formed by the inverter turn-off circuit. An input filter is, therefore, necessary.

Description

The filter consists of a number of capacitors connected in parallel across the input terminals of the d-c to d-c converter. At the kilocycle inverter switching frequency for Task A, the lightest weight capacitors are similar to the type utilized for inverter commutating purposes. They are made of aluminum foil with ML dielectric and enclosed in aluminum cans. The characteristics of this type of capacitor are shown in Table 2.

With the Task B inverter circuit operating at a relatively lower switching frequency than the inverter circuit of Task A, aluminum electrolytic capacitors were selected for the much larger value of capacitance required for the Task B input filter. The use of electrolytic capacitors for Task B results in a substantial filter weight saving compared to the use of the ML type.

A fuse for each capacitor prevents failure of the filter if a short-circuit occurs within a capacitor. Fuses capable of operating in a space environment will probably require development.

Operation

The input filter serves two functions during the commutating interval of the inverter. During the first part, the action of the commutating circuit causes the inverter to demand current in excess of the normal load current. The input filter supplies this surge. At the end of the first part of the commutating interval, there is a certain amount of energy "trapped" in the commutating inductors. This energy is fed back to the power source during the second part of the commutating interval. Since it has been assumed that the thermionic diodes cannot accept power, the filter must store the "trapped" energy. Hence, the input filter capacitor discharges during the first part of the commutating interval and charges during the second part.

TABLE 2

PRELIMINARY CAPACITOR CHARACTERISTICS, TASK A

Dielectric Material	<u>1968 (estimated)</u> Aromatic Polyimide Dupont (ML)	<u>1963</u> Polycarbonate
Conductor	Foil	Metallized
Density of Winding	0.05 lb/cu in.	0.06 lb/cu in.
Rated Max. Temperature	250°C	120°C
Dissipation Factor	0.1% at 1 kilocycle	0.1% at 1 kilocycle
<u>Bulk Factor of Uncased Capacitor:</u>		
<u>Mfd. x Volts/Cu. In.</u>	<u>Operating Voltage</u>	Same as 1968
70	100	
118	200	
152	400	
182	600	
190	800	
195	1000	
198	1200	
200	1400 and up	

NOTE: These are estimated characteristics of devices not now available.

Design Criteria

1. The thermionic source cannot accept power; therefore, the voltage across the source terminals during commutation may be allowed to reach but not exceed the normal open circuit source voltage.
2. The dynamic characteristic of the thermionic source is the same as its static volt-ampere characteristic.
3. The filter capacitance was calculated on the basis that all trapped energy is returned to the filter and that the capacitor voltage rise is limited to 15 volts above the nominal value in accepting this energy.

In the interest of minimum weight, the smallest possible filter capacitance is used, consistent with the requirements of the inverter circuits. It may be that other considerations, such as thermionic diode heating due to ripple current, or suppression of radio frequency interference would dictate larger values of capacitance, resulting in more filter weight.

Conceptual Data

The value of filter capacitance required in Task A to suppress the input voltage peaks to 15 volts above the normal source voltage of 150 volts is 350 microfarads. Using 400 volt, 250°C ML capacitors, Table 3 shows power loss, component weight, space volume, and efficiency. Filter data are shown for the 30-kw converter and are totaled for 102 identical, electrically isolated converters for the 3.25-mw system. The energy loss for the filter of Task A is approximately 0.005 joules per cycle; the variation of losses with inverter switching frequency is shown in Figure 6. For reasons presented in the latter part of this section of the report, the power losses at 2300 cycles per second are used in Table 3.

The energy storage requirements for commutation of the relatively slow switching vapor tube thyratrons used in the Task B converter are much greater than that for silicon controlled rectifiers. Therefore, the energy returned to the input filter is much greater. Limiting the rise in source voltage after commutation to 15 volts requires approximately 4000 microfarads of filter capacitance. Since this would result in 628 pounds of the ML type capacitors, aluminum electrolytic capacitors weighing 14 pounds were selected.

TABLE 3

INPUT FILTER DATA FOR 30-KW CONVERTER,
TASK A AND TASK B

	Task A	Task B
Capacitor Type	Aromatic Polyimide Dupont ML	Aluminum Electrolytic
Total Filter Capacitance (mfd)	350	7680
Total Qty. Capacitors	7@50 mfd each	16@480 mfd each
Capacitor Voltage Rating (volts)	400	400
Total Capacitor Losses (watts)	11 (1)	40
Total Capacitor Weight (lb.)	46 (e. s. w.)(2)	14
Total Capacitor Space Volume (in. ³)	920 (e. s. v.)(3)	283

INPUT FILTER DATA FOR 3.25-MW CONVERTER SYSTEM

Total Capacitor Losses (watts)	1122	4080
Total Capacitor Weight (lb.)	4692 (e. s. w.)(2)	1428
Total Capacitor Space Volume (in. ³)	93840 (e. s. v.)(3)	28866
Input Filter Efficiency (%)	99.9	99.86

NOTE: The totals for the 3.25-mw converter system are the results of 102 electrically isolated 30-kw converters.

(1) Losses resulting from Figure 6, at 2300 cps.

(2) Uncased capacitor weight.

(3) Uncased capacitor volume.

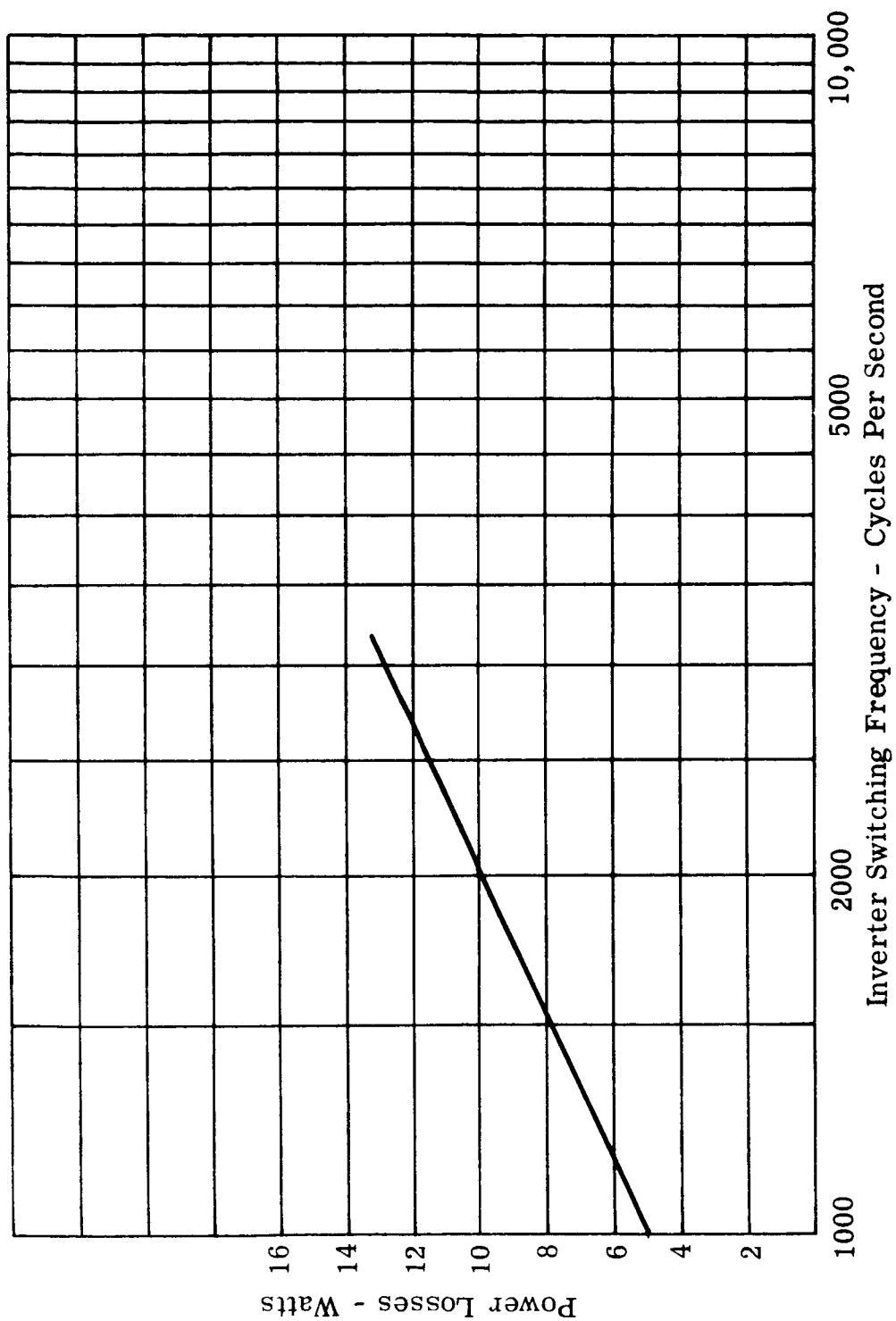


FIGURE 6

Input Filter

Power Losses Per 30-kw Converter Vs. Inverter Switching Frequency, Task A

Analysis of the operating characteristic of the Task B inverter shows that at the upper limit of source voltage, approximately 40 amperes rms ripple current flows in the input filter. Electrolytic capacitors have a definite current limitation which becomes the major factor in determining the filter size. The unit capacitor selected for Task B is rated at 480 microfarads at 400 volts d-c, with a maximum ripple current capability of 2.5 amperes at 85°C. Since the ripple current is 40 amperes, 16 units are required for a total of 7680 microfarads.

Table 3 presents the conceptual data for the Task B filter. It is to be expected that the filter power loss for Task B would increase with increasing inverter frequency according to Figure 6.

Problem Areas

The major problem in evaluating input filters is the lack of precise information regarding the characteristics of the thermionic source. The previous assumptions provide a basis for study, but it is not known whether these assumptions are realistic.

Secondary to the above problem is the fact that exact solutions for filter capacitance and power loss are practically impossible to obtain analytically and are best found experimentally. Since the experimental approach is impossible at this time, the filter values have been determined by approximate methods.

Recommendations

1. Evaluation of input filter parameters should be carried out by experimental means in advance of the time that flight hardware is specified.
2. Ways to reduce input filter weight should be investigated because the input filter amounts to a large fraction of the weight of the power conversion equipment. One method would be to operate several small converters out of phase with one another, from one common source, as in Tasks C and D of this study.

2. Inverter Switching Circuit

The single-phase inverter circuit was selected for conceptual study because it provides a minimum weight converter system². The inverter

² "Space Electric Power Systems Study," Vol. 5, Final Report, prepared by Westinghouse Electric Corporation, for National Aeronautics and Space Administration, Contract NAS5-1234, Amendment 6, May 3, to December 3, 1963.

circuits for the Task A and Task B converters are shown in Figure 7. Transformers shown in the figure are not part of this functional block; they are considered separately in the following discussion. Controlled rectifier and diode properties shown in Tables 4 through 6, used in this study, are not available today. They represent the best estimates of what will be available in 1968. The physical and electrical characteristics of the vapor tube thyatron and gas tube diode were obtained through NASA Lewis, Cleveland, Ohio and from previous work performed on Contract NAS5-1234, Amendment 6. The capacitors used in the inverter circuits have the same characteristics as those used for the input filter in Table 2.

The conventional single-phase bridge inverter circuit was initially selected for the Task B converter. This circuit has high efficiency, low regulation, and tolerance to a wide range of load power factors. Besides the stated advantages, use of the bridge circuit was necessary because it applies minimum forward voltage across the thyatron when it is in the non-conducting state. With a 150 volt d-c input from the nuclear-thermionic source, the voltage across the 200 volt rated thyatron, under normal operation will be 150 volts.

The bridge circuit is desirable since it is capable of providing a pulse-width modulated output and therefore the voltage control and inversion functions can be accomplished simultaneously. Because an analytical treatment of the regulating mode of operation was not available in the literature, it was necessary to perform the inverter circuit analysis with the use of an analog computer.

During normal operation of the conventional circuit when full pulse-width is produced, excess energy trapped in the inductors is transferred to the load through the feedback diodes and the tapped power transformer primary. However, when the bridge is modulated, as accomplished on the computer, the voltage applied to the power transformer assumes zero potential during some portion of the cycle. With zero potential on the transformer primary, the energy trapped in the inductors cannot be transferred to the load. If the excess energy in the inductors is not completely removed during the remaining portion of the half cycle, the current circulates through the thyatrons and diodes and causes excessive losses. The value the current assumes is determined by the circuit losses and can be calculated by equating the energy losses every half cycle and the energy added by the commutating capacitors every half cycle. Since the currents in the thyatrons are increased, the length of time that the thyatrons are reverse biased by the commutating components is decreased. This affects the size of the commutating components adversely, increasing the converter size and weight.

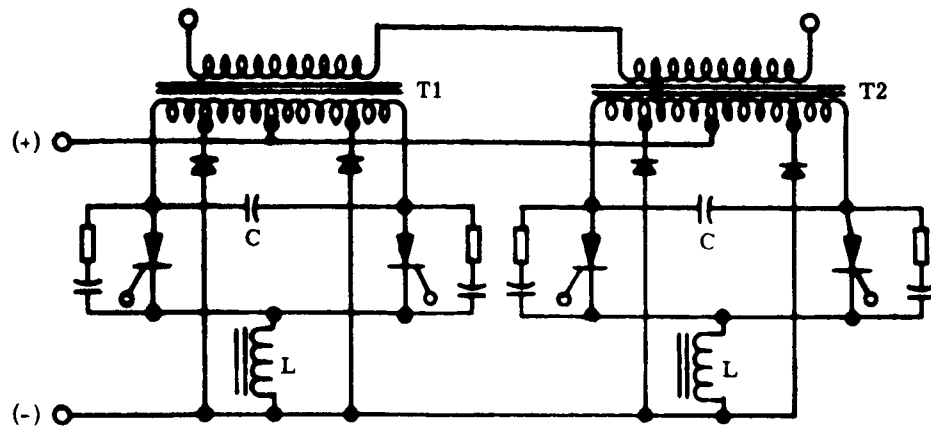


Figure a.

Task A Inverter Circuit

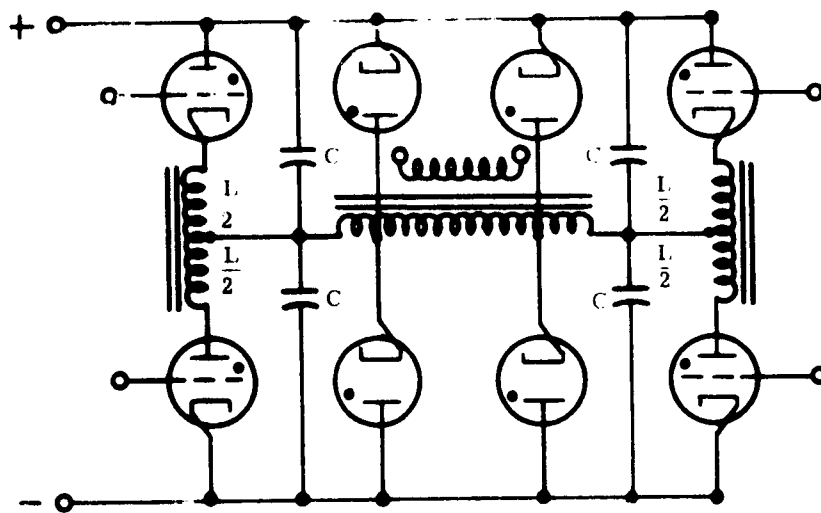


Figure b.

Task B Conventional Bridge Inverter Circuit

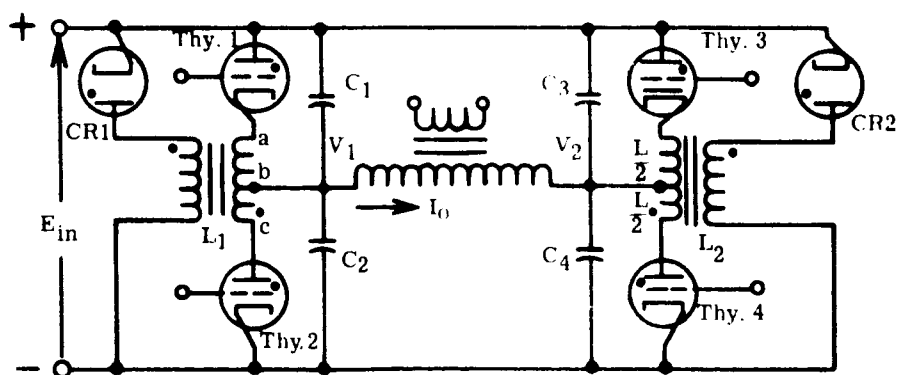


Figure c.

Task B Modified Bridge Inverter Circuit

FIGURE 7.

Inverter Switching Circuit Schematic Diagrams, Task A and Task B

TABLE 4

PRELIMINARY SILICON CONTROLLED RECTIFIER
CHARACTERISTICS, TASK A

Reverse Voltage (volts)	1000
Voltage Drop	Similar to (W) Type 200H
Current Rating (rms, amps)	250
Turn-Off Time (microseconds)	
I = 50 amps	15
I = 100 amps	20
Turn-On Time (microseconds)	1.5
Gate Voltage, Max. at $T_j = 25^\circ\text{C}$ (volts)	2.5
Gate Current, Max. at $T_j = 25^\circ\text{C}$ (milliamps)	100
Mechanical Package	Similar to (W) Type 200H
Junction Temperature, Max. ($^\circ\text{C}$)	150

NOTE: These are estimated characteristics as this device is not now available.

TABLE 5
PRELIMINARY VAPOR TUBE THYRATRON
CHARACTERISTICS, TASK B

Frequency, Max. (cps)	3200
Forward Voltage Rating (volts)	200
Voltage Drop (volts)	2 to 3
Current Rating (rms, amps)	250
Deionization Time (microseconds)	100
Ionization Time (microseconds)	10
Filament Power (watts)	25
Size	3 in. Dia. x 6 in. Ht.
Weight (lb.)	1
Envelope Temperature, Max. (°C)	600

NOTE: These are estimated characteristics as this device is not now available.

TABLE 6
PRELIMINARY GAS TUBE DIODE CHARACTERISTICS,
TASK B

Frequency, Max. (cps)	3200
Reverse Voltage (kv)	4.5
Voltage Drop (volts)	15 to 20
Current Rating (rms, amps)	16
Filament Power (watts)	50
Deionization Time (microseconds)	100
Ionization Time (microseconds)	10
Diode Length (inches)	7
Diode Diameter (inches)	4.5
Diode Weight (pounds)	1.5
Envelope Temperature, Max. (°C)	800

NOTE: These are estimated characteristics as this device is not now available.

Figure 8 represents the computer results of the major thyatron parameters confirming the preceding discussion. The data were obtained for the conventional bridge circuit with a voltage-current source characteristic as described by Figure 4 at an inverter frequency of 1000 cycles per second. With a varying pulse-width modulating angle, the thyatron current on the left half of the bridge is seen to increase from 500 to a maximum of approximately 1060 amperes at 90 degrees. With a 1000 cycle per second inverter frequency, the thyatron 200 volt forward rating was exceeded for the entire 90 degree pulse-width modulating range. From Figure 8, it is also seen that the thyatron reverse bias time becomes inadequate (less than the rated 100 microseconds) when the modulating angle increases beyond approximately 79 degrees.

Appendix A gives the analog computer programing information including converter schematic diagram, circuit describing equations, analog diagrams, truth statements, thyatron logic, potentiometer settings, and circuit parameters.

To remove the excess energy from the commutating inductors during the entire half cycle by some means that is not dependent on the power transformer voltage, has resulted in the modified bridge inverter circuit of Figure 7 c. This circuit was used to determine the conceptual data for the Task B converter.

Circuit Description and Operation

The controlled rectifiers (silicon , vapor tube) shown in Figure 7 receive alternating signals from the drive amplifiers. In response to the drive signals, the controlled rectifiers turn on and off alternately, thus applying d-c voltage alternately to the transformer primary. When the controlled rectifiers conduct for a time interval equivalent to a half cycle, this action induces a square wave voltage in the transformer secondary.

The voltage of the inverter output is proportional to the d-c voltage supplied by the nuclear-thermionic power source. With the source voltage greater than normal, the output voltage of the inverter will have a tendency to rise. To counteract this tendency, by voltage control, drive signals are applied to the controlled rectifiers in a manner that will maintain the rectified d-c voltage within the proper limits by pulse-width modulation. The result is that the switching devices cause the alternating voltage induced into the transformer secondary to deviate from a square wave into a quasi-square wave. Therefore, the greater the tendency for voltage rise in the rectified output, the shorter the current conducting pulses (for each half period) permitted to flow through the transformer secondary.

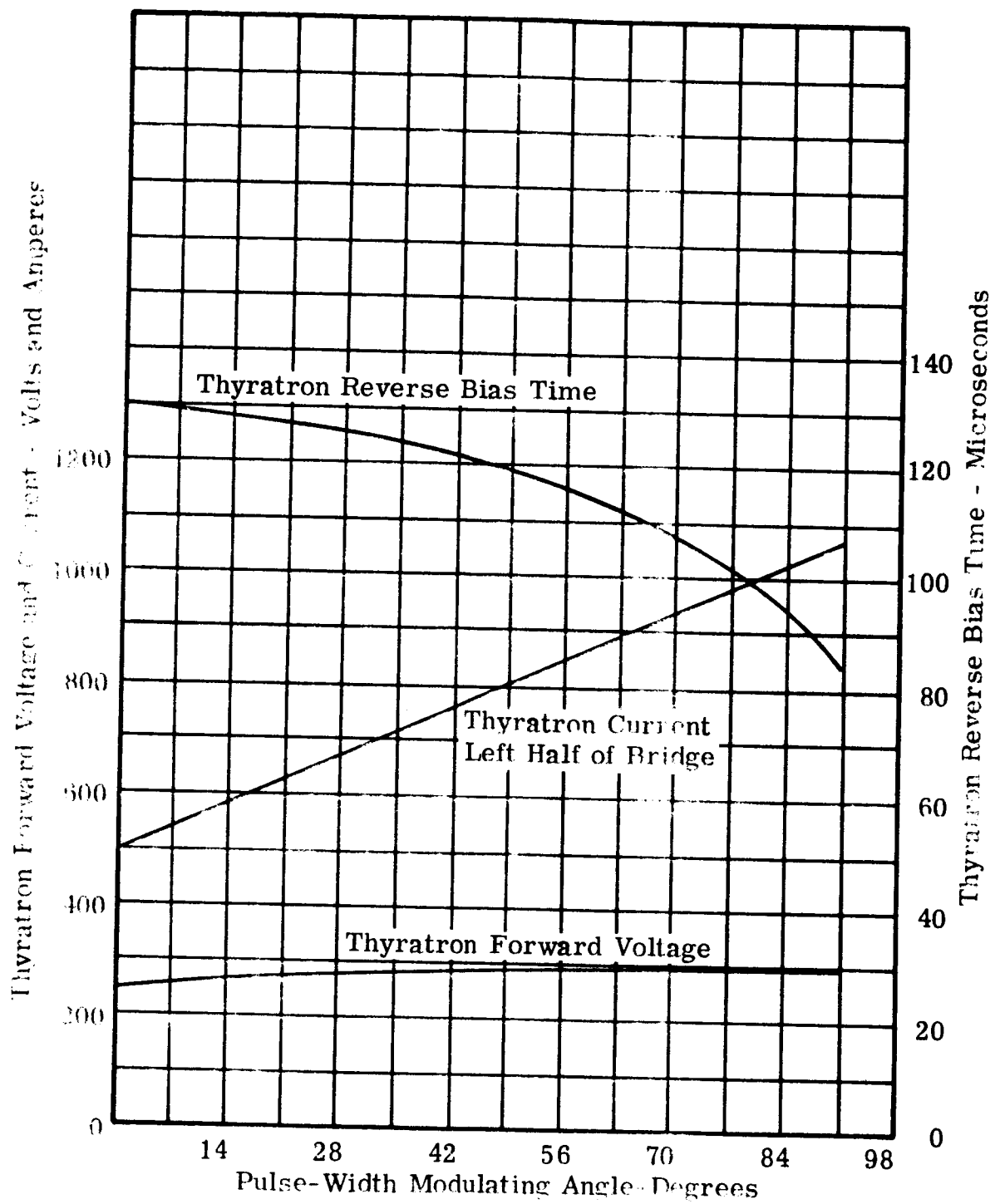


FIGURE 8

Vapor Tube Thyatron Parameters In Conventional
Bridge Inverter Circuit, Task B

The basic silicon controlled rectifier inverter module of Figure 7 a, used in the NAS5-1234, Amendment 6 study, has been retained for the Task A converter. Detailed operation of the individual inverter modules has been presented in the literature.³ Voltage modulation in this application is achieved by connecting the output transformer secondaries of the individual modules in series and phase-shifting the alternating voltage of one inverter circuit with respect to the other. This is accomplished by two separate sets of phase-shifted drive signals. With commutating components of equal size in each module, the inverter can operate at full controlled rectifier conduction. If, in other applications where this is not required or desired, slight weight reduction appears possible by eliminating the commutator inductor and reducing the commutating capacitance in one of the inverter modules. Current turn off will be affected by the first inverter module.

In the inverter circuit for Task B, voltage regulation is accomplished by time delaying the drive signals to one side of the bridge switching devices with a circuit similar to the one used for the Task A inverter. The resulting voltage control method for the Task B converters, therefore, is similar to that used with the Task A converters.

Operation of the Task B inverter, which is unique and therefore does not appear in the literature, is as follows. Assume that all diode and thyatron voltage drops are negligible and that thyatrons 1 and 4 are conducting. The current through thyatron 1 and 4 is I_0 amperes. The potential V_1 is E_{in} volts, N_1 of the inductors = secondary turns/turns from the center tap to either end, and V_2 is $-E_{in}/N_1$ volts. The inductor $L_1 = L_2$ and $C_1 = C_2 = C_3 = C_4$. At $t = 0$ thyatron 1 is turned on.

Referring to Figure 7 c, the potential V_1 is applied from point b to point c on L_1 . The cathode of thyatron 1 is driven to $+2 E_{in}$ volts which reverse biases thyatron 1 by E_{in} volts. The current I_0 , which was flowing through the upper half of L_1 now flows in the lower half. The potential V_1 drops and when it reaches $E_{in}/2$ the reverse bias on thyatron 1 is lost. The voltage V_1 continues to drop until it reaches $-E_{in}/N_1$ at which time the commutating period ends. The current through L_1 has increased to approximately $2 I_0$ for the choice

³ McMurray, W. and D. P. Shattuck, "A Silicon Controlled Rectifier Inverter with Improved Commutation." AIEE Transactions, Part I, Communications and Electronics, Vol. 80, November 1961, p. 531-542.

of L_1 and C_1 outlined in Messrs. McMurray and Shattuck's technical paper. The potential ($V_1 - V_2$) is zero and the load voltage is zero. With the resistive load rectifier coupled to the power transformer secondary, the load current becomes zero. The current flowing in the inductor represents energy stored in the inductor ($E = 1/2 LI^2$). This energy is returned to the input filter capacitor from the secondary winding through diode CR1. Since the voltage on the secondary can be no greater than E_{in} , the voltage reflected to the primary is E_{in}/N_1 . When thyatron 3 is turned on, thyatron 4 is turned off by the same sequence of events previously described and the potential V_2 rises to $E_{in} (1 + 1/N_1)$. The voltage applied to the primary is then $(V_1 - V_2) = -E_{in} (1 + 2/N_1)$ and energy is transferred to the load. Energy is removed from L_1 until it is equal to $1/2 LI_0^2$. At this time, the voltages across L_1 become zero because the total di/dt of the current through L_1 is zero. The value of the current through thyatron 2 is once again I_0 and remains at this value until thyatron 1 is turned on which initiates the positive half cycle of operation. The positive half cycle is identical to the negative half cycle except the roles of the thyatrons are interchanged (i. e., thyatron 1 turns off thyatron 2, etc.).

Design Criteria

The major components used in this study are types not available today. The power switches, diodes, and capacitors are advanced units whose characteristics have been estimated. The estimated characteristics of the components to be available in 1968 have been resolved through consultations with component suppliers and NASA. The characteristics are based on normal industry progress and are intended to be realistic estimates of what will be available in 1968.

To help assure long life, components are operated at less than their maximum ratings. Operating levels of voltage and current are generally one-half the rated values and operating temperatures are held to 75% or less of the rated maximum temperatures. Complying with NASA's direction, neither voltage nor temperature derating were applied to the vapor tube thyatrons or gas tube diodes of the Task B inverter circuit.

The inverter for Task A was evaluated over the switching frequency range of 1000 to 3200 cycles per second. From work performed on NAS5-1234, Amendment 6, it was anticipated that this range would encompass all practical designs. The lower switching frequencies have the advantage of reducing losses in the switching elements, but high frequencies result in less transformer weight.

The inverter circuit for Task B was evaluated only at a frequency of 200 cycles per second. This became necessary because at frequencies above 200 cycles per second, at a source voltage of 150 volts, with the inverter operating in a pulse-width modulated voltage regulating mode, the thyatron voltage rating of 200 volts is exceeded.

Other considerations used to prepare the conceptual data for the inverter circuits are presented in the following assumptions.

- a. The converter must maintain rated output voltage at $\pm 5\%$ at full load with a $\pm 10\%$ variation in d-c input voltage.
- b. The converters must withstand open or short circuit faults at the high voltage bus without damage. The full load operating point of the nuclear-thermionic source is such that maximum open circuit voltage will not exceed the component voltage ratings.
- c. The converters are required to operate at no more than 1.25 per unit load current on short-circuit faults.

Conceptual Data:

Tables 7 and 8 list the component rating, power losses, weight, and efficiency for the inverter circuits of the Task A and Task B converters. Results have also been tabulated for the 3.25-mw converter system.

The curve of Figure 9 shows the increasing trend in the Task A inverter circuit losses with increasing frequency. The increase in power loss with increasing frequency is influenced by the controlled rectifiers and the voltage suppressor components. The major power loss in the inverters, however, occurs in the switching devices in the form of forward voltage drop and switching losses. At low frequencies the forward drop is predominant, but as frequency increases, the switching loss becomes more important.

Problem Areas:

The high temperature thyatron converter poses two major problems. It was assumed that the high temperature vapor tubes would have characteristics somewhat similar to low temperature gas tube thyatrons, specifically that they could be turned on by grid control but could only be turned off by interrupting the anode current. Thus, they would require a capacitor to store energy for turn-off.

TABLE 7

INVERTER CIRCUIT DATA FOR 30-KW CONVERTER, TASK A

Inverter Circuit Frequency (cps)	1000	1800	2000	2200	3200
D-C Input Voltage (volts)	150	150	150	150	150
<u>Inductor</u>					
Inductance/Module (microhenries)	30.2	30.2	30.2	30.2	30.2
Total Losses (watts)	152	152	152	152	152
Total Electromagnetic Wt (lb)	2.72	2.72	2.72	2.72	2.72
<u>Capacitor</u>					
Capacitance/Module (microfarads)	18.4	18.4	18.4	18.4	18.4
Total Losses (watts)	87.4	87.4	87.4	87.4	87.4
Total Electrostatic Wt (lb)	8.6	8.6	8.6	8.6	8.6
<u>Silicon Controlled Rectifier</u>					
Type	Similar to (W) Type 200H, except 1000V, 250A.				
Total Losses (watts)	401	452	465	478	542
Total Wt (lb)	3	3	3	3	3
<u>Diode</u>					
Type	Similar to (W) Type 700P				
Total Losses (watts)	246	246	246	246	246
Total Wt (lb)	0.64	0.64	0.64	0.64	0.64
<u>Voltage Suppressor Circuit</u>					
Total Losses (watts)	37.	66.7	74.1	81.5	118.3
Total Wt (lb)	0.7	0.7	0.7	0.7	0.7
Total Inverter Losses (watts)	923.4	1004.1	1024.5	1044.9	1145.7
Total Inverter Wt (lb)	15.66	15.66	15.66	15.66	15.66

INVERTER CIRCUIT DATA FOR 3.25-MW CONVERTER SYSTEM

Total Inverter Losses (kw)	94.1	102.4	104.5	106.5	116.8
Total Inverter Wt (lb)	1597	1597	1597	1597	1597
Inverter Efficiency (%)	97.0	96.7	96.69	96.63	96.3

NOTE: The totals for the 3.25-mw converter system are the results of 102 electrically isolated 30-kw converters.

TABLE 8

INVERTER CIRCUIT DATA FOR 30-KW CONVERTER, TASK B

Inverter Circuit Frequency (cps)	200
D-C Input Voltage (volts)	150
<u>Inductor</u>	
Inductance/Unit (2 units)(microhenries)	120
Total Losses (watts)	372
Total Electromagnetic Wt (lb)	54. 2
<u>Capacitor</u>	
Capacitance/Unit (4 units)(microfarads)	382
Total Losses (watts)	101
Total Electrostatic Wt (lb)	194. 5
<u>Vapor Tube Thyatron</u>	
Rating	200 Volts, 250 Amps
Total Losses (watts)	968. 4
Total Wt (lb)	4
<u>Gas Tube Diode</u>	
Rating	4. 5 KV, 16 Amps
Total Losses (watts)	373
Total Wt (lb)	3
Total Inverter Losses (watts)	1814. 4
Total Inverter Wt (lb)	255. 7

INVERTER CIRCUIT DATA FOR 3. 25-MW CONVERTER SYSTEM

Total Inverter Losses (kw)	185.
Total Inverter Wt (lb)	26, 050
Inverter Efficiency (%)	94. 3

NOTE: The totals for the 3. 25-mw converter system are the results of 102 electrically isolated 30-kw converters.

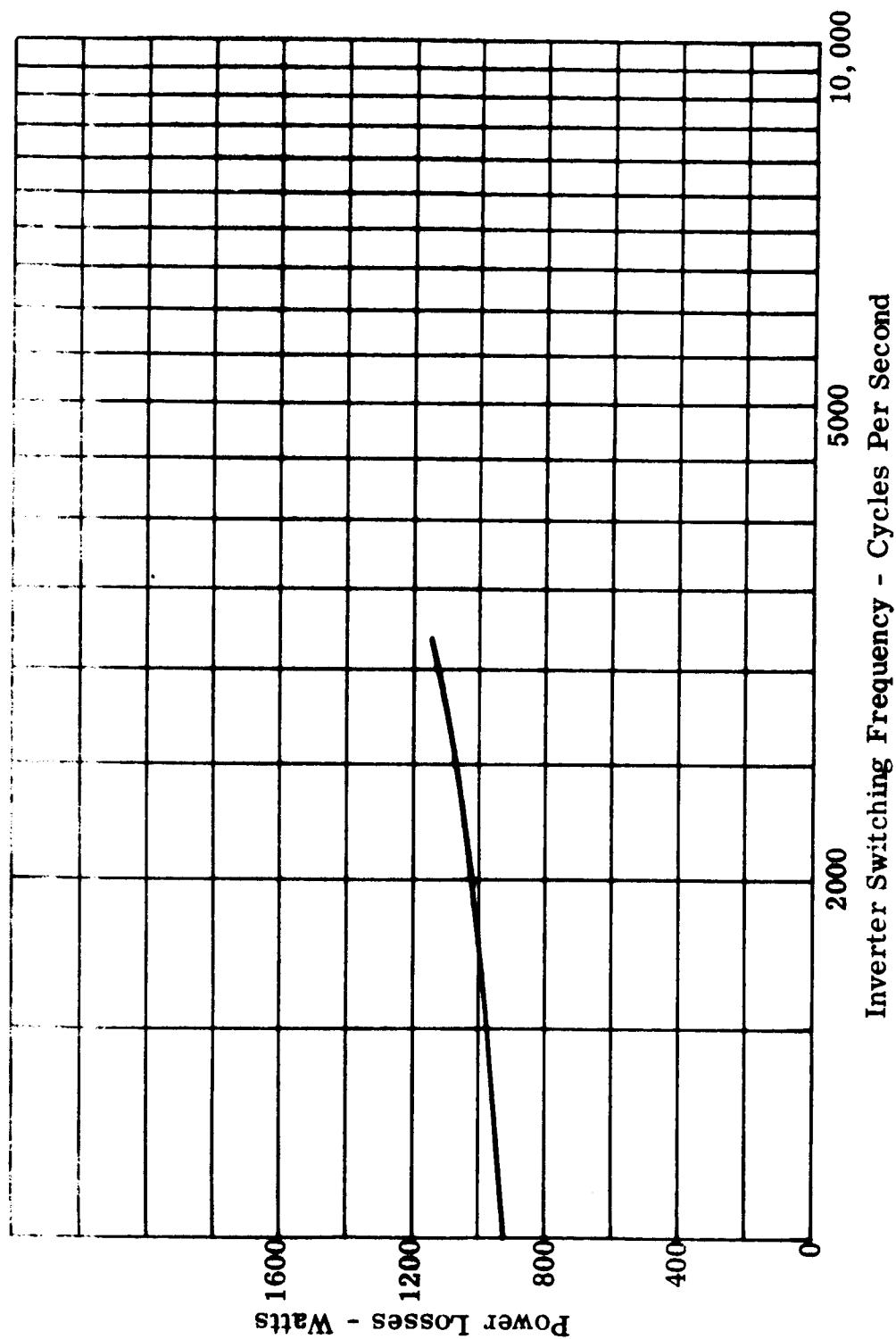


FIGURE 9

Inverter Circuit Power Losses Per 30-kw Converter Vs. Inverter Switching Frequency,
Task A

One problem is that capacitors capable of withstanding the 600°C envelope temperatures proposed for the tubes are not available. The highest temperature capacitors now available are usable to about 300°C and weigh about five times as much as units designed for lower temperatures. Sufficient improvement is not expected in these properties by 1968 if normal trends are followed.

The problem was circumvented for purposes of this study by using low temperature (250°C) capacitors and providing a cooling system that is thermally isolated from the high temperature cooling system. However, a high temperature capacitor would result in a lighter, simpler system.

A second problem that arises in connection with high temperature vapor tubes is that of supplying power to the filaments. Because a-c power is not available, the customary filament transformers cannot be used. It is necessary to provide a source of regulated d-c, probably at a low voltage. This requires a device capable of regulating low d-c voltages at high current levels and operating at high temperature.

Analysis and Recommendations

The inverter circuit data for Task A (in Table 7) show that efficiency decreases as the frequency increases.

This is a natural consequence of the increase in switching losses with frequency displayed by all switching elements. The resulting efficiency presented in Tables 7 and 8 shows that the vapor tube thyatron used in the Task B inverter circuit is less efficient than the silicon controlled rectifier circuit used for Task A. This occurs primarily because the thyatrons have a relatively high voltage drop during conduction compared to their voltage rating.

The one component which contributes the most weight to the inverters is the commutating capacitor. In the case of the Task B inverter, it becomes very significant. The commutating capacitance value for the inverters, shown as a separate entity in the circuit schematics, is directly proportional to the switching device turn-off time and conducting load current and is inversely proportional to the input voltage. Since the thyatron has a deionization time that is approximately five times the turn-off time of the silicon controlled rectifier, its commutating capacitance is proportionally greater. The Task B converter input voltage and corresponding current with the source at its minimum limit, is such that less capacitance is required for the Task B inverter than for the

Task A inverter. This is offset by the difference in inverter circuits with four times as much capacitance required for each capacitor of the Task B inverter circuit as for the Task A.

To aid in reducing power losses and weight, the following recommendations apply to the Task B converters.

- a. High temperature vapor tube thyratrons should be developed for higher voltage ratings than now proposed with input source voltages of 150 volts or greater. This will permit the use of other circuits and will aid in reducing commutating capacitance requirements and/or permit operation at higher inverter frequency.
- b. An attempt should be made to develop high temperature vapor tube thyratrons with deionization times considerably less than the 100 microseconds now proposed. This permits efficient operation at higher frequencies and reduces capacitance requirements, thus reducing not only inverter weight but the weight of power transformers and filters as well.
- c. Capacitors are required as filtering and commutating elements in high temperature inverters. It would be desirable to develop capacitors that are capable of operating at a case temperature of 600°C with a dissipation factor of less than 1%, and size and weight comparable to ordinary paper capacitors. There has been very little demand for such units in the past, but the demand will increase as more power equipment for space applications is planned.
- d. Attention should be given to the problems of providing regulated low voltage d-c power to the filaments of the proposed high temperature tubes and of making the tubes capable of operating for long periods with d-c filament power.

The following recommendations are intended to enhance the advantages of controlled rectifiers for this specific application.

- a. Develop silicon controlled rectifiers capable of operating for extended periods at higher temperatures than presently available devices. A rating of 200°C would be desirable even if it resulted in poor operation at temperatures below 0°C.

- b. Develop silicon controlled rectifiers with faster turn-off times at high temperature than present units. Turn-off times of the order of 5 to 10 microseconds at 100 amperes and 150°C junction temperatures would be a worthwhile improvement.
- c. It is desirable to determine the effects of nuclear radiation on silicon controlled rectifiers and to attempt to manufacture devices that are more radiation resistant than present devices.

3. Power Transformers

The purpose of the transformer is to increase the voltage magnitude of the inverter circuit square waves or quasi-square waves so that after rectification the output is the rated direct voltage. The selection of a single-phase transformer was dictated by the choice of the single-phase inverter circuit.

The transformer conceptual data for Task A have been prepared using two 15-kva units, whereas Task B uses one 30-kva unit for each of the 102 electrically isolated 30-kw converters.

Description

The power transformers for Task A and Task B are similar. Each of the transformers uses two separate cores in a shell-type configuration. The transformers consist of single primary and secondary windings with the primary for the Task A units center tapped. The conceptual data for these transformers are based on copper conductors and tape wound silicon iron cores.

Design Criteria

The transformer designs are based on the following assumptions.

- a. The conductor is copper and losses are based on 100% conductivity, standard annealed copper at 500°C.
- b. Because of a lack of data on magnetic iron losses with a square wave input, losses are assumed to be the same as for a sine wave input.
- c. Insulation was provided for the dielectric requirements based on 100 volts per mil through the insulation and 25 volts per mil creepage.

- d. The temperature rise characteristics of the separate units are maintained at approximately the same level.

Conceptual Data

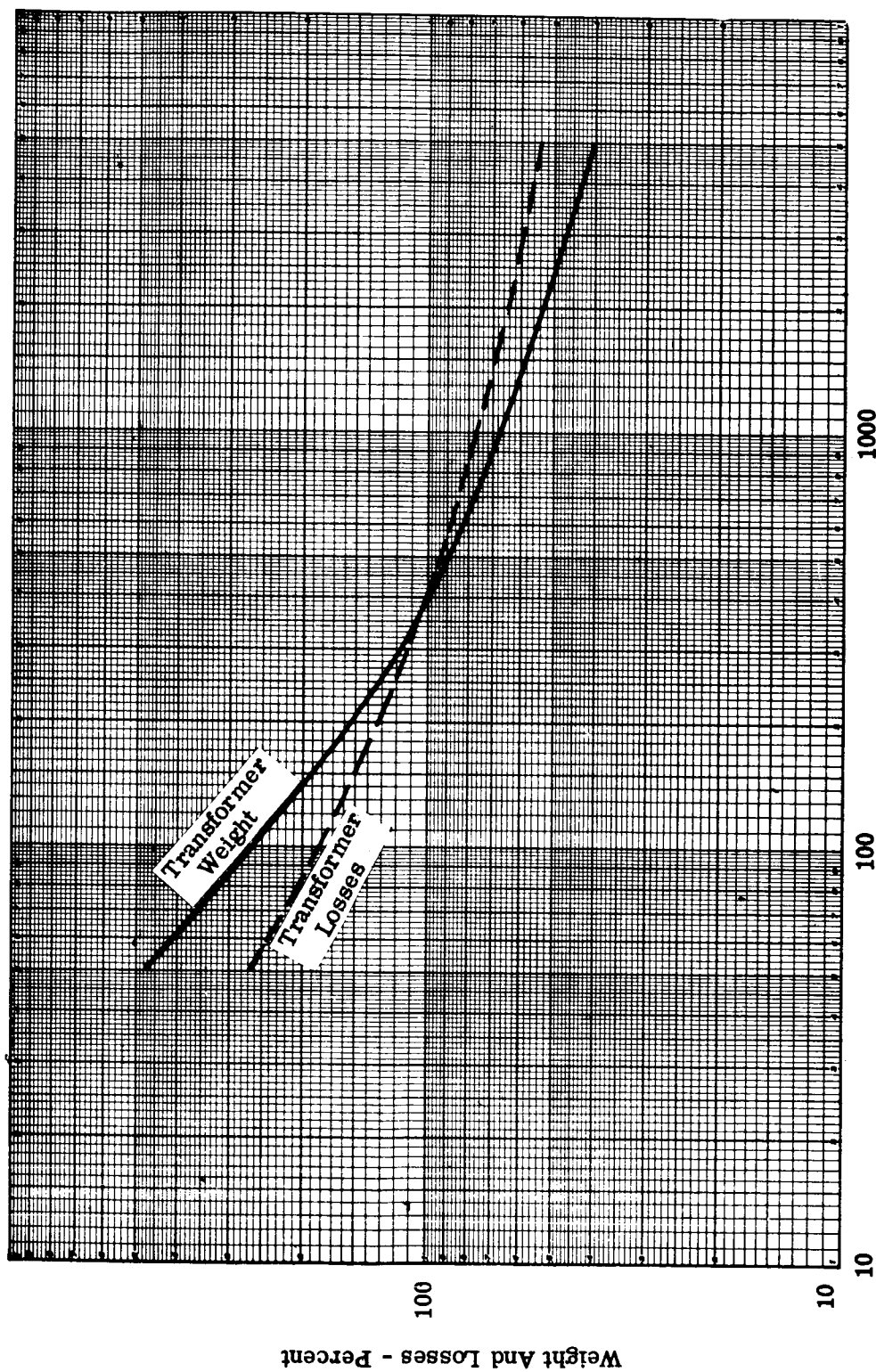
The curves of Figure 10 show the variation of weight and losses for individual inverter power transformers for frequencies from 50 to 5000 cycles per second. Figure 11 shows the variation of transformer weight and losses per kva for different transformer kva ratings. These figures were reproduced from Figures 28 and 29 of the Space Electric Power Systems Study, Volume 5, Contract NAS5-1234, Amendment 6. The information from these curves forms the basis for the tabulated transformer data of this study. Tables 9 and 10 present the data for the power transformers of Task A and Task B, respectively. Table 9 shows the unit rating, the number of units, losses, weight, and space volume for an inverter switching frequency range of 1000 to 3200 cycles per second. The curve of Figure 12 shows the trend in transformer losses for the 30-kw rated converter of Task A as a function of inverter switching frequency. The values in Table 10 for the Task B transformers are shown for 200 cycles per second only because of the limitations of the inverter circuit vapor tube thyratrons. Transformer losses, weight, and space volume are totaled in the tables to show the requirements for 102 identical, electrically isolated 30-kw converters for the 3.25-mw system.

Problem Areas

Little is known of transformer material service life and dielectric strength of insulating materials at elevated temperatures. It is generally realized that the useful life of a transformer is greatly reduced when its operating temperature is extended beyond its designed rating. Because the higher temperature-rated transformers will require new materials, new manufacturing processes and techniques are also required. Therefore, the application of transformers to operate at high temperature extremes (600°C) with high reliability and extended service life involves unknown factors of design, manufacture, and material capability.

Analysis and Recommendations

As seen from Figure 10 and Table 9, transformer weight and losses decrease with increasing frequency. This shows that a transformer designed for a specific kva rating and frequency will be capable of delivering more power, at the same weight, at a higher frequency.



Inverter Switching Frequency - Cycles Per Second

FIGURE 10

Transformer

Relative Weight and Losses Vs. Inverter Switching Frequency

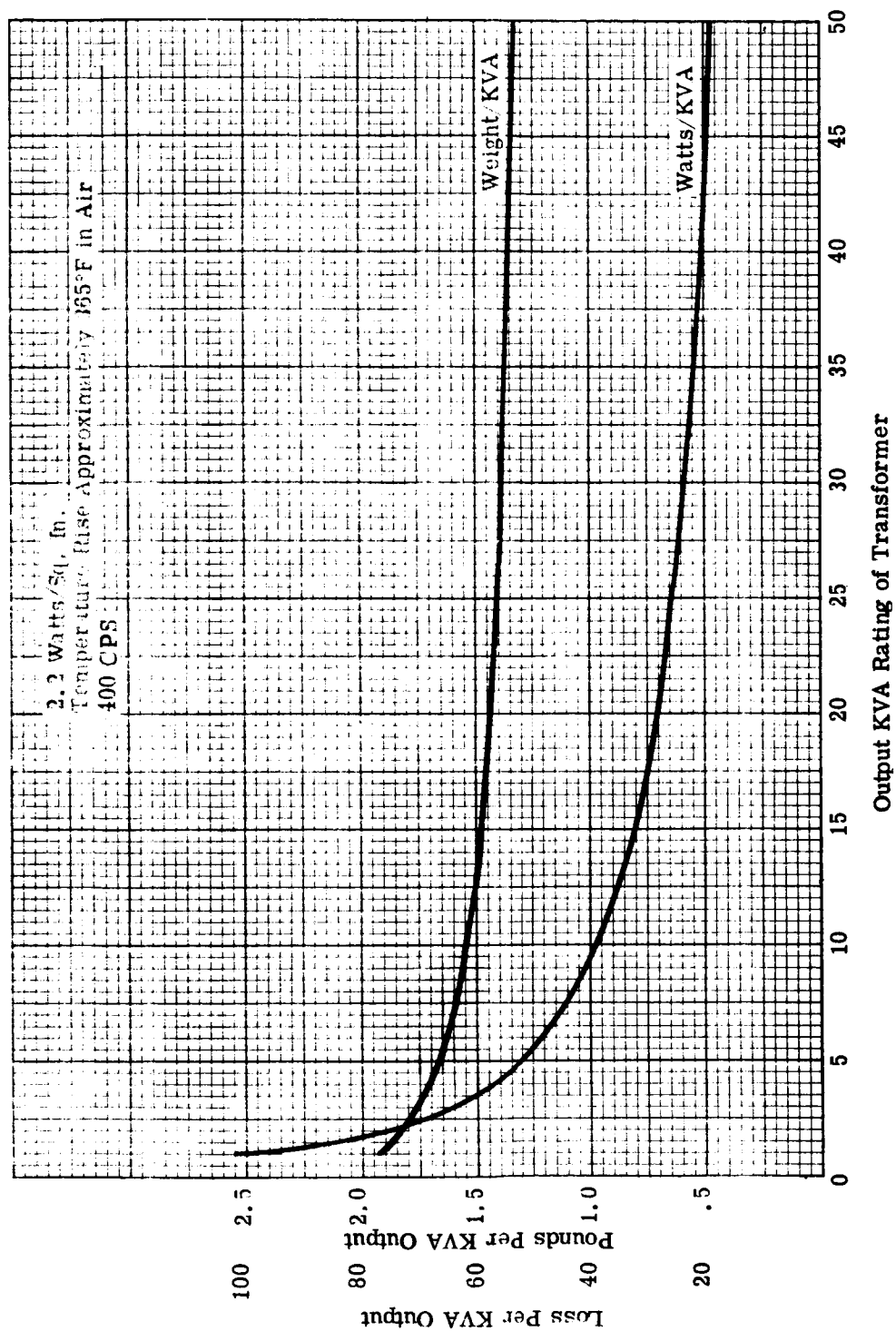


FIGURE 11
Transformer
Specific Weight and Losses Per KVA vs. KVA Rating

TABLE 9

POWER TRANSFORMER DATA FOR 30-KW CONVERTER, TASK A

Inverter Circuit Frequency (cps)	1000	1800	2000	2200	3200
Transformer Rating (kva)	15	15	15	15	15
Watts Loss/Transformer	370	317	312	303	280
Electromagnetic Wt./Transformer (lb.)	14.9	12.2	11.8	11.4	10.2
Space Volume/Transformer (in. ³)	148	118	115	108	96
Number Transformers	2	2	2	2	2
Total Transformer Losses (watts)	740	634	624	606	560
Total Transformer Wt. (lb)	29.8	24.4	23.6	22.8	20.4
Total Transformer Space Vol (in. ³)	296	236	230	216	192

POWER TRANSFORMER DATA FOR 3.25-MW CONVERTER SYSTEM

Total Transformer Watts (kw)	75.48	64.67	63.65	61.81	57.12
Total Transformer Wt. (lb)	3040	2489	2407	2326	2081
Total Transformer Vol (in. ³ x 10 ³)	30.2	24.1	23.5	22.0	19.6
Transformer Efficiency (%)	97.58	97.93	97.96	98.02	98.16

NOTE: The totals for the 3.25-mw converter system are the results of 102 electrically isolated 30-kw converters.

TABLE 10

POWER TRANSFORMER DATA FOR 30-KW CONVERTER,
TASK B

Inverter Circuit Frequency (cps)	200
Transformer Rating (kva)	30
Watts Loss/Transformer	938
Electromagnetic Wt/Transformer (lb)	63.8
Space Volume/Transformer (in. ³)	588
Number Transformers	1
Total Transformer Losses (watts)	938
Total Transformer Wt (lb)	63.8
Total Transformer Space Vol (in. ³)	588

POWER TRANSFORMER DATA FOR 3.25-MW CONVERTER SYSTEM

Total Transformer Watts (kw)	95.68
Total Transformer Wt (lb)	6508
Total Transformer Space Vol (in. ³ x 10 ³)	59.98
Transformer Efficiency (%)	96.96

NOTE: The totals for the 3.25-mw converter system are the results of 102 electrically isolated 30-kw converters.

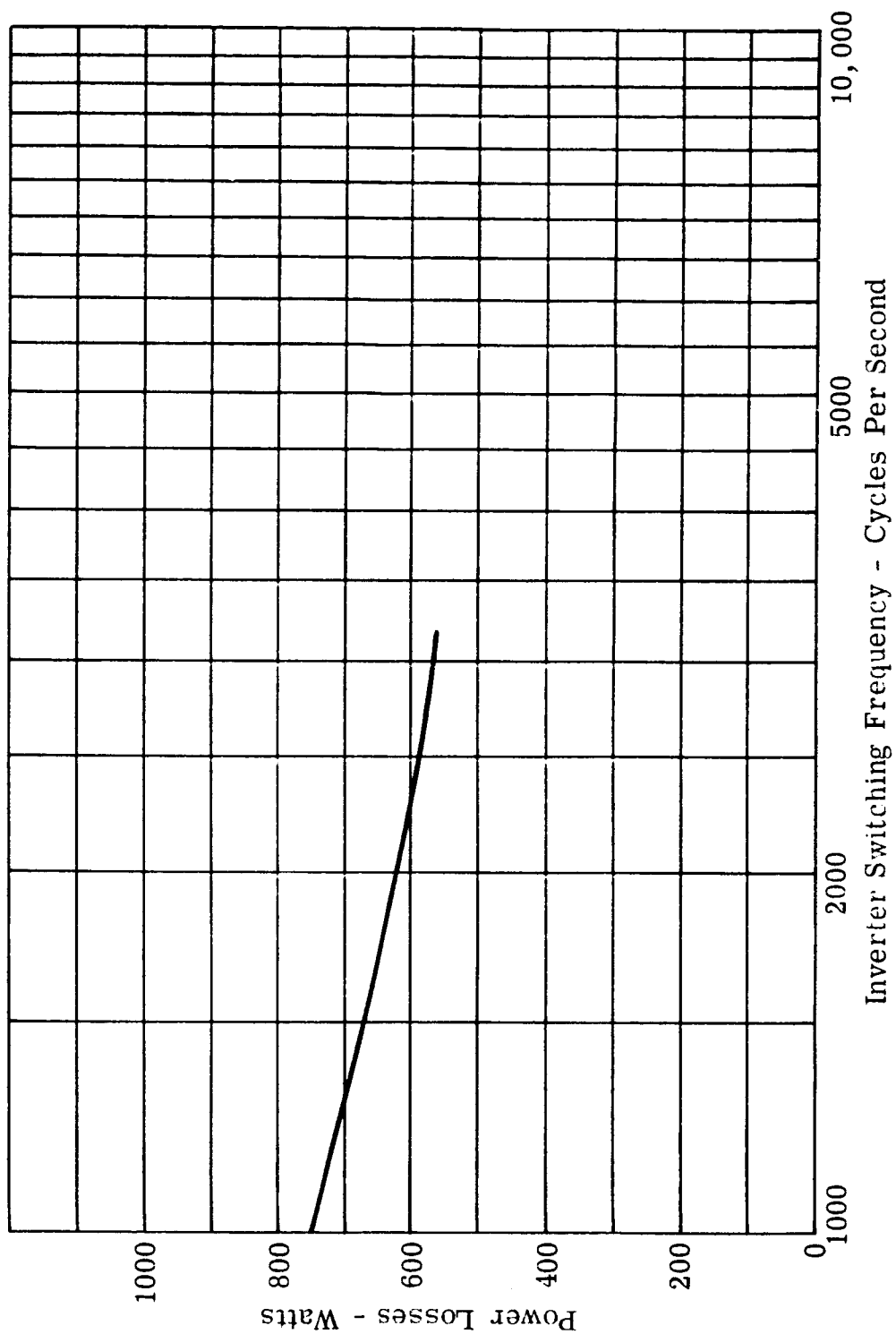


FIGURE 12

Transformer Power Losses Per 30-kw Converter Vs. Inverter Switching Frequency, Task A

As shown in Figure 11, transformer weight (in pounds per kva) and losses (in watts per kva) for the same input conditions, decrease with increase in kva rating. However, the 30-kva transformer of Task B weighs more and is less efficient than the two 15-kva units of Task A because of its lower operating frequency.

The NASA Lewis Laboratory, through contracts NAS3-4162 and NAS3-6465, is engaged in basic materials and compatibility studies on insulations, conductors, magnetics, and bore seals at elevated temperatures and low pressures. It is recommended that the above studies be followed by new programs which will permit the design, development, and evaluation of practical full scale transformers and other magnetic core devices for space and similar applications.

4. Power Rectifier

As in the case of the power transformer, the choice of the single-phase inverter circuit dictated the selection of single-phase rectification. The rectifier conceptual data were prepared using a single-phase full-wave bridge. The rectifier bridge circuit is preferred and was selected for conceptual study because it permits a power transformer of smaller size for the same d-c power delivered to the load.

The conceptual data for the rectifier assemblies of Task A were prepared using silicon diodes. Rectifier data for the converters of Task B were prepared using high temperature gas tube diodes.

Circuit Description

The schematic circuit of the bridge rectifier is shown in Figure 13. Each leg of the rectifier assembly is made up of several silicon avalanche diodes in series for the converter of Task A. The number of series diodes required is dependent upon the peak inverse voltage (PIV) rating of the individual diodes. Voltage division across the series silicon avalanche diodes of the rectifier assembly is accomplished by shunting each diode with a capacitor. The reverse voltage-current characteristics of the avalanche diode make it possible to omit a shunting resistor used with conventional high voltage series diode rectifier assemblies. Because single unit gas tube diodes can be made in kilovolt ratings, only one diode is required per leg for the rectifier of Task B.

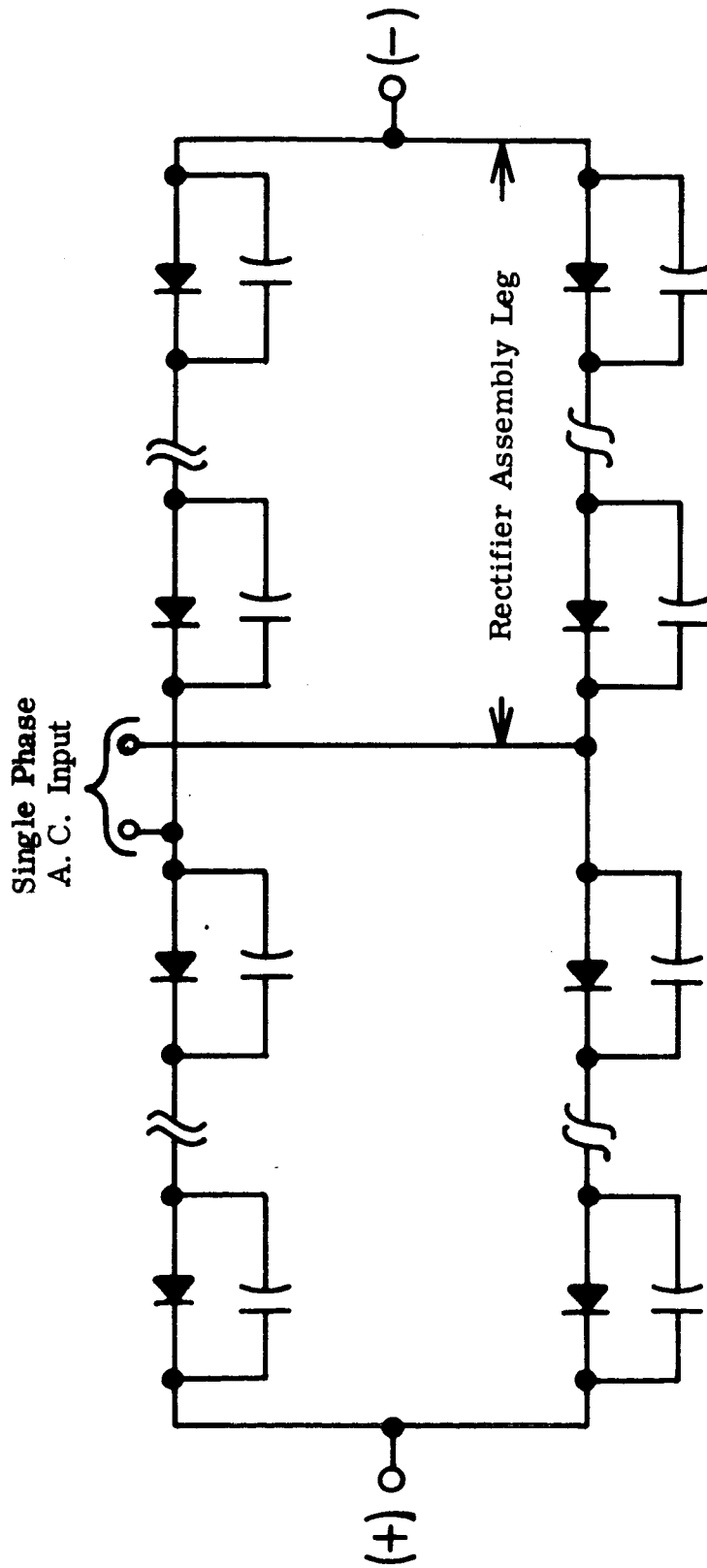


FIGURE 13

Single-Phase Rectifier Bridge Schematic Circuit, Task A and Task B

Design Criteria

To calculate the conceptual data, several design guide lines and basic assumptions are made as follows. The intent is to predict rectifier assemblies based on the characteristics of diodes available in 1968.

- a. The number of silicon diodes per rectifier bridge was determined by requiring that the diode peak inverse voltage (PIV) rating be at least 2.5 times the PIV seen by each diode under normal operation. This factor of 2.5 allows for voltage transients, unbalance between diodes and voltage balancing components, and adequate derating for long life and permits safe operation with some shorted diodes. According to NASA's direction, a voltage derating was not applied to the gas tube diodes.
- b. The current rating of the silicon diodes is based on a minimum overload capacity of 400 percent for one second. This rating is adequate as determined from the electrical characteristics of the nuclear-thermionic space power plant.
- c. Diode manufacturers have indicated that semiconductor diode losses are essentially unaffected by operating frequencies up to 5,000 cycles per second. This is particularly true of diffused junction diodes. Therefore, frequency is not considered in the computation of semiconductor rectifier losses.

Frequency was considered in the diode switching losses of the gas tube rectifier assembly. Calculations were performed at an inverter frequency of 200 cycles per second.

Semiconductor diode losses were calculated on the basis of using a junction temperature of 131°C , which is a 25% derating from the supplier's specified maximum of 175°C . The gas-tube diodes were assumed to operate with a heat rejection temperature of 600°C .

- d. Avalanche silicon diodes are now available in PIV ratings of 1200 volts. It was assumed that normal improvements in the state-of-the-art by 1968 will permit diode ratings of 3000 PIV. Diode ratings of 3000 PIV were used in this study.

The voltage rating of the gas tube diode selected for this application is 7700 volts at 4.25 amperes, rms. The tube voltage rating was determined from the peak voltage ripple at maximum open circuit source voltage. The physical and electrical characteristics of the gas tube diode were obtained through NASA Lewis, Cleveland, Ohio and from the previous work performed on contract NAS5-1234, Amendment 6. (See Table 11.)

- e. The capacitor voltage rating is at least equal to the individual silicon diode PIV rating at a capacitor body temperature of 115°C. This, therefore, is at least 2.5 times the peak working voltage seen by each capacitor under normal system operation. Capacitor losses were calculated for the frequency extremes of 1000 to 3200 cycles per second for the semiconductor rectifier system of Task A. Capacitors are not necessary for the converter rectifier assembly of Task B.
- f. It is assumed that the filament power for the gas tube diodes is obtained at the proper voltage potential directly from the nuclear-thermionic source. It is further assumed that the tube filament voltage requirements will be maintained as necessary.

Conceptual Data

Tables 12 and 13 list the component quantities, power losses, weight, space volume, and conversion efficiency for the rectifier assemblies of the 30-kw converters of Tasks A and B. Data are also tabulated for the 3.25-mw converter system.

The curve of Figure 14 shows the trend in rectifier losses for the 30-kw converter of Task A as a function of inverter switching frequency. The increase in power loss with increasing frequency is caused by the voltage balancing capacitors only.

Problem Areas

The application of practical rectifier assemblies in d-c to d-c converters requires an investigation into the characteristics which can influence system operation.

TABLE 11
PRELIMINARY GAS TUBE DIODE CHARACTERISTICS,
TASK B

Frequency, Max. (cps)	3200
Reverse Voltage (kv)	7.7
Voltage Drop (volts)	15 to 20
Current Rating (rms, amps)	4.25
Filament Power (watts)	50
De-ionization Time (microseconds)	100
Ionization Time (microseconds)	10
Diode Length (inches)	7
Diode Diameter (inches)	3
Diode Weight (pounds)	1
Envelope Temperature, Max. (°C)	800

NOTE: These are estimated characteristics as this device is
not now available.

TABLE 12

RECTIFIER ASSEMBLY SILICON DIODE DATA FOR 30-KW
CONVERTER, TASK A

Inverter Circuit Frequency (cps)	1000	1800	2000	2200	3200
D-C Bus Volts (kv)	5	5	5	5	5
Load D-C Amperes	6	6	6	6	6
Diode					
Amps. /1Ø Bridge	6	6	6	6	6
Avg. Amps. /Diode	3	3	3	3	3
Diode PIV	3000	3000	3000	3000	3000
Diodes/1Ø Bridge	24	24	24	24	24
Diode Type	Controlled Avalanche, 12 Amps., Except 3000 PIV				
Total Diode Loss (watts)	64.8	64.8	64.8	64.8	64.8
Total Diode Wt (lb)	0.375	0.375	0.375	0.375	0.375
Total Diode Space Vol (in. ³)	6	6	6	6	6
Capacitor					
Shunt Capacitor (mfd)	0.005	0.005	0.005	0.005	0.005
Total Qty. Capacitors	24	24	24	24	24
Total Capacitor Watts	10.1	18	20.2	22.1	32.2
Total Capacitor Wt (lb)	0.46	0.46	0.46	0.46	0.46
Total Capacitor Space Vol (in. ³)	3.6	3.6	3.6	3.6	3.6
Total Rectifier Losses (watts)	74.9	82.8	85	86.9	97
Total Rectifier Wt (lb)	0.835	0.835	0.835	0.835	0.835
Total Rectifier Space Vol (in. ³)	9.6	9.6	9.6	9.6	9.6

SILICON DIODE RECTIFIER ASSEMBLY DATA FOR
3.25-MW CONVERTER SYSTEM

Total Rectifier Losses (kw)	7.64	8.45	8.67	8.85	9.89
Total Diode Wt (lb)	85.2	85.2	85.2	85.2	85.2
Total Diode Space Vol (in. ³)	979	979	979	979	979
Rectifier Conversion Eff. (%)	99.75	99.72	99.71	99.7	99.67

NOTE: The totals for the 3.25-mw converter system are the results of 102 electrically isolated 30-kw converters.

TABLE 13

RECTIFIER ASSEMBLY GAS TUBE DIODE DATA FOR
30-KW CONVERTER, TASK B

Inverter Circuit Frequency (cps)	200
D-C Bus Volts (kv)	5
Load D-C Amperes	6
Amps. /1Ø Bridge	6
Avg. Amps. /Diode	3
Diode PIV	7700
Diodes/1Ø Bridge	4
Diode Type	Gas Tube, 800°C Capability
Diode Filament Power (watts)	50
Total Diode Loss (watts)	712
Total Diode Wt (lb)	4
Total Diode Space Vol (in. ³)	50

GAS TUBE DIODE RECTIFIER ASSEMBLY DATA FOR
3.25-MW CONVERTER SYSTEM

Total Diode Loss (kw)	72.6
Total Diode Weight (lb)	408
Total Diode Space Vol (in. ³)	5100
Rectifier Conversion Efficiency (%)	97.8

NOTE: The totals for the 3.25-mw converter system are the results of 102 electrically isolated 30-kw converters.

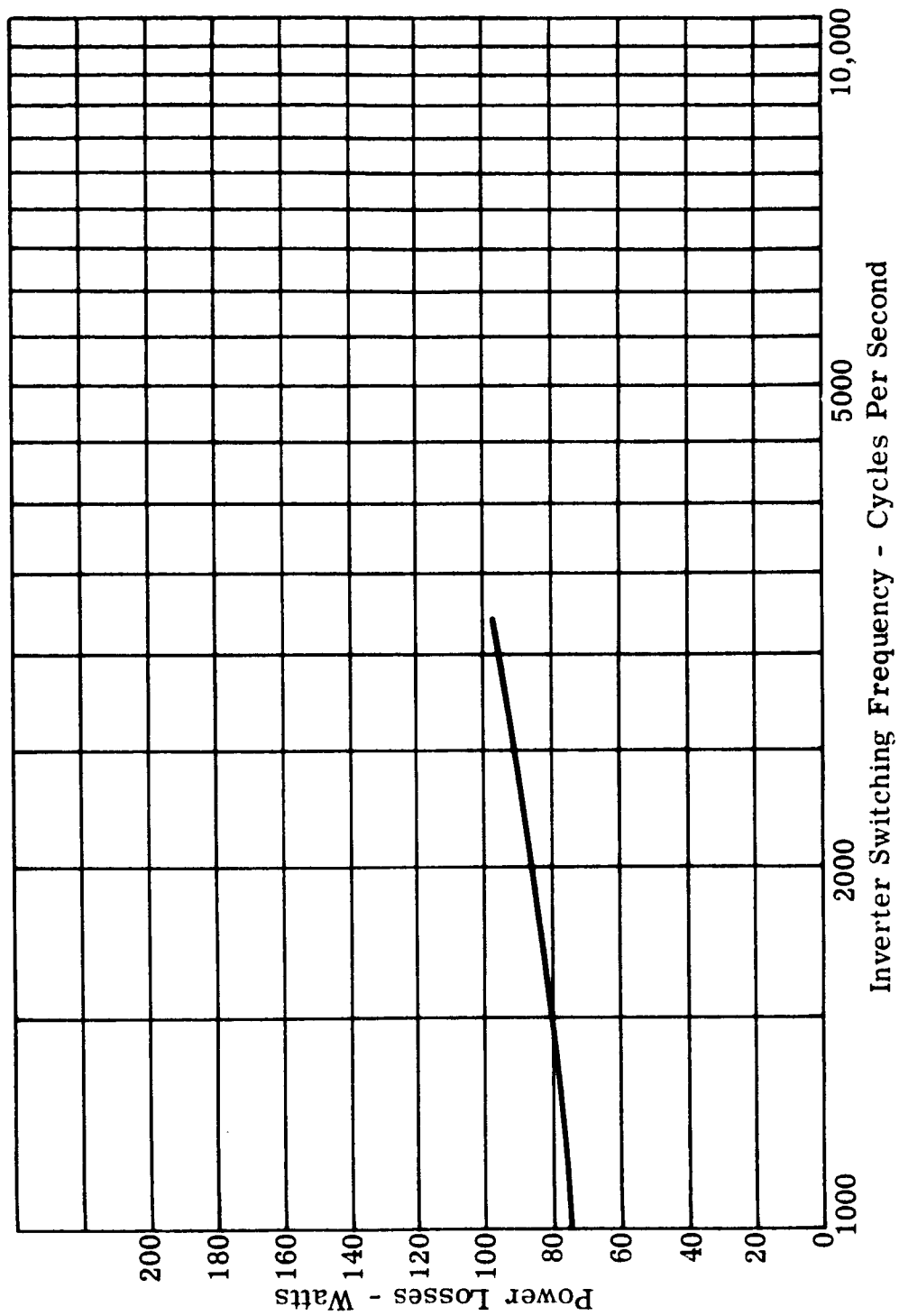


FIGURE 14

Silicon Diode Rectifier Assembly Power Losses Per 30-kw Converter Vs.
Inverter Switching Frequency, Test A

a. Radio Interference

Rectifier equipment is a source of radio noise that is generated by the diodes in their normal commutation of load current. The presence of radio frequency currents and voltages in the d-c output circuit may cause interference in communication circuits exposed to the load circuit. The radio-frequency harmonics in the d-c output can be reduced to ineffective values by means of a series reactor and shunt element such as a capacitor or several combinations of resonant reactor-capacitors.

b. Voltage Transients

Voltage transients as high as eight times the normal peak reverse voltage may be reflected across the rectifiers when the primary circuit of a transformer-rectifier is opened. This transient voltage is created when the transformer magnetizing current and flux collapse suddenly coupling high voltage into the transformer secondary. The voltage transients may be reduced by the use of diodes with two or three times the normal peak reverse voltage of the system combined with capacitor suppressor circuits.

c. Gas Tube Diode Filament Requirements

A potential problem area is foreseen with the use of gas tube diodes as the rectifying elements. These tubes require a separate filament power source of approximately 50 watts for each tube when heat rejection temperature is at 600°C. It is assumed that the filament power source is d-c taken directly from the nuclear-thermionic generator. The tube filament voltage requirements, which will probably be less than 5 volts, must be regulated within $\pm 5\%$ to maintain satisfactory tube operation and life. Therefore, a high temperature gas tube rectifier assembly would require a high temperature low voltage regulating circuit.

Analysis and Recommendations

As seen from Table 12, the silicon semiconductor rectifier assembly offers a conversion efficiency in excess of 99% for all of the inverter frequencies considered. It was assumed that normal

advancement in the state-of-the-art as dictated by economics will see the increase of silicon semiconductor voltage ratings to 3000 PIV by 1968.

This voltage rating was used in preparing the conceptual data for this study.

From Table 13, it is seen that the gas tube rectifier assembly conversion efficiency, at 200 cycles per second, is in excess of 97%. Should these rectifying elements appear feasible for this application, it is recommended that study and development be expended to reduce the given de-ionization time of 100 microseconds. Reduction of the diode de-ionization and ionization time will reduce the power losses or permit operation at increased frequency with the same losses. Operation at higher frequency would aid in reducing transformer and output filter size and weight. The 200-cycle-per-second frequency limitation for the gas tube diode rectifier assembly is not because of a short coming in the diode but as stated earlier in the inverter circuit discussion, is dictated by the vapor tube thyatron characteristic.

Because the use of gas tube diodes will require filament voltage regulation, probably within $\pm 5\%$, it is recommended that the study and development of voltage regulator tubes, under contract NAS3-2548, be made compatible with the gas tube diode filament requirements.

5. Output Filter

Output filters are necessary for the converters of Task A which use semiconductor controlled switches and rectifying diodes and for the converters of Task B which use high temperature vapor tube thyatron switches and gas tube rectifiers. The conceptual data for these filters were prepared using an inductance-capacitance circuit.

Design Operation and Circuit Description

The purpose of the output filter is to reduce the voltage ripple on the rectified d-c bus to a value which is compatible with the requirements of the load.

The filter selected for this study is a conventional low pass inductance-capacitance network which is of the inductance input type with the capacitor in shunt across the load. It has the advantage of providing relatively good voltage regulation, high transformer utilization factor, and low diode peak currents.

For the filter selected, the capacitor reactance is usually smaller than the load impedance. This causes the alternating components of current to be shunted past the load. Also, the capacitive reactance is almost always lower than the inductive reactance, so that the ripple voltage appears across the inductor and not across the capacitor and load.

Design Criteria

The filter conceptual data are based on the following.

- a. The ripple voltage, which is reduced to a minimum level of 4% rms, is the only criterion used to determine the filter parameters. This value agrees with NASA's present requirements for electric propulsion engine circuits.
- b. The capacitor voltage rating is at least 2.5 times the peak capacitor voltage under normal system operation. The capacitor dielectric is film-plus paper.
- c. The capacitor case temperature is maintained at 95°C, which is a 25% derating from the supplier's specified maximum of 125°C.
- d. The inductor losses are based on a temperature that results from using a liquid metal cooling system with inlet temperatures in excess of 371°C.

Conceptual Data

The output filter parameters for the converters are determined from the rms voltage ripple values calculated from the rectified inverter output waveforms. This permits the calculation of the necessary attenuation to obtain the desired output ripple voltage. To restrict the selection of the numerous L-C filter combinations to a single choice, it was necessary to use an additional constraint. Therefore, in addition to the attenuation requirements, the low pass L-C filter was required to meet the damping factor of one at full rated load. This latter condition was reflected as the ratio of L-C as a function of resistive load.

The data for the output filters of Task A and Task B are presented in Tables 14 and 15, respectively. Filter data are shown for the 30-kw converter and are totaled for 102 identical, electrically isolated converters for the 3.25-mw system. The filter data of Table 14 for Task A show the power loss, weight, and space

TABLE 14

OUTPUT FILTER DATA FOR 30-KW CONVERTER,
TASK A

Inverter Circuit Frequency (cps)	1000	1800	2000	2200	3200
D-C Bus Volts (kv)	5	5	5	5	5
D-C Load Current (amps)	6	6	6	6	6
<u>Capacitor</u>					
Capacitance (mfd)	0.2	0.11	0.1	0.09	0.07
Total Qty. Capacitors	4	2	2	2	2
Total Capacitor Losses (watts)	1	0.9	1	1.1	1.61
Total Capacitor Wt (lb)	2	1	1	1	1
Dimensions/Capacitor	Dia. = 1.344", Lgth. 5.75"				
<u>Inductor</u>					
Inductance (millihenries)	555	302	278	250	194
Inductor Losses (watts)	475	360	345	328	290
Inductor Electromagnetic Wt (lb)	22.5	14	13	12	9.8
Inductor Space Vol (in. ³)	180	107	98	90	72
Total Filter Losses (watts)	476	360.9	346	329.1	291.6
Total Filter Wt (lb)	24.5	15	14	13	10.8
Total Filter Space Vol (in. ³)	212.6	125.3	116.3	108.3	90.3

OUTPUT FILTER DATA FOR 3.25-MW CONVERTER SYSTEM

Total Filter Losses (kw)	4.86	3.68	3.53	3.36	2.97
Total Filter Wt (lb)	2500	1530	1428	1326	1102
Total Filter Space Vol (in. ³ x 10 ³)	21.7	12.8	11.88	11.05	9.21
Filter Efficiency (%)	98.43	98.81	98.85	98.91	99.03

NOTE: The totals for the 3.25-mw converter system are the results of 102 electrically isolated 30-kw converters.

TABLE 15

**OUTPUT FILTER DATA FOR 30-KW CONVERTER,
TASK B**

Inverter Circuit Frequency (cps)	200
D-C Bus Volts (kv)	5
D-C Load Current (amps)	6
<u>Capacitor</u>	
Capacitance (mfd)	1. 1
Total Qty. Capacitors	22
Total Capacitor Losses (watts)	1. 11
Total Capacitor Wt (lb)	11
Dimensions/Capacitor	Dia. = 1. 344", Lgth. = 5. 75"
<u>Inductor</u>	
Inductance (henries)	3
Inductor Losses (watts)	1030
Inductor Electromagnetic Wt (lb)	84
Inductor Space Vol (in. ³)	780
Total Filter Losses (watts)	1031. 1
Total Filter Wt (lb)	95
Total Filter Space Vol (in. ³)	960

OUTPUT FILTER DATA FOR 3. 25-MW CONVERTER SYSTEM

Total Filter Losses (kw)	105. 2
Total Filter Wt (lb)	9690
Total Filter Space Vol (in. ³ x 10 ³)	98
Filter Efficiency (%)	96. 5

NOTE: The totals for the 3. 25-mw converter system are the results of 102 electrically isolated 30-kw converters.

volume for inverter switching frequencies of 1000 to 3200 cycles per second. The values in Table 15 for the Task B filters are shown only for 200 cycles per second because of the limitations of the inverter circuit vapor tube thyatron. The trend in filter losses for the 30-kw converter of Task A, as a function of frequency, is shown in Figure 15.

Problem Areas

The inductors of the output filter are capable of being cooled by liquid metal coolants at temperatures in excess of 371°C. Capacitors capable of operating at this coolant temperature are not available and probably will not be available by 1968 at the present normal rate of development. For this application this problem was circumvented by using 125°C capacitors with an appropriate cooling system which are isolated from the high temperature inductor system.

Analysis and Recommendations

Voltage ripple on an unfiltered converter d-c output bus increases with increasing inverter frequency because the off time of the inverter circuit output voltage waveshape, as influenced by the switching device turn-on and turn-off times, becomes a greater part of the voltage output wave. This, therefore, results in a relatively poorer quality waveform.

The voltage ripple and attenuation requirements for the Task A and Task B converters are comparable. Task A uses an inverter switching device which is faster, thereby making it possible to operate at a higher frequency whereas Task B uses a slower operating switching device necessitating a reduced frequency. The net result is that both the Task A and Task B inverter output voltage waves, from a percentage standpoint, have an approximately equivalent off time compared to the on time. Although the voltage ripple increases with increasing inverter switching frequency, the filter size, weight, and losses decrease with increasing frequency because both capacitance and inductance requirements become less. This is illustrated in the Tables 14 and 15.

To provide a filter capacitor cooling system which is compatible with the operating temperature of the inductor, it is desirable to develop capacitors capable of operating at 371°C coolant temperatures. These capacitors should be capable of operating at a dissipation factor of approximately one percent and with a bulk factor approaching that of the existing lower voltage, lower temperature capacitors.

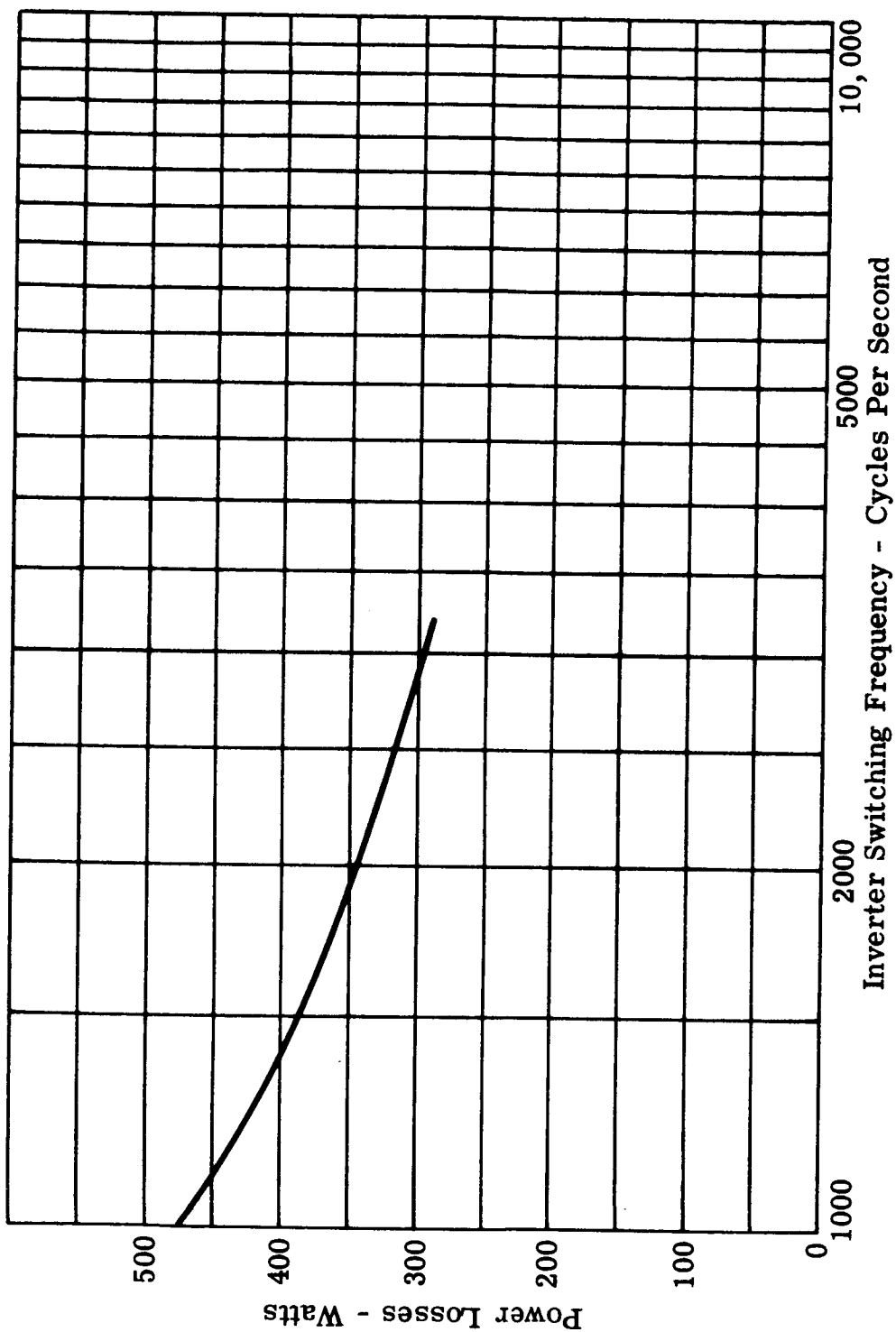


FIGURE 15
Output Filter Power Losses Per 30-kw Converter Vs. Inverter Switching Frequency, Task A

6. Frequency Reference Oscillator

The frequency-reference oscillator determines the operating frequency of the inverter circuit. It is not a constant-frequency device. Rather, its frequency varies in direct proportion to its input voltage. Since the oscillator obtains its input voltage from a tap whose voltage is some fraction of the source voltage, the oscillator output frequency is proportional to the converter input main-bus voltage. This varying frequency is desirable because it prevents saturation of the power transformers at higher than nominal input voltage. The nominal frequency of the power conversion system is fixed by the design of the frequency reference oscillator and is maintained only as long as the nominal input voltage is maintained.

Description

Figure 16 represents the circuit of the frequency reference oscillator. The basic elements are the saturable transformer and the two transistors, Q7 and Q8.

The auxiliary circuit consisting of R23, C5, and CR16 is provided to turn on the controlled rectifier, CR17, which is shown in the schematic of the voltage regulator circuit. The function of CR17 is discussed in the voltage regulator section of this report.

Operation

The operation of this circuit has been thoroughly described in the literature. Briefly, it is as follows. When power is applied, one of the main transistors starts to turn on. Its collector current, flowing through the transformer, induces a voltage in the feedback winding which drives the transistor into full conduction. This state continues until the transformer saturates, whereupon the other transistor starts to conduct and the first one turns off. The result is a square wave a-c output which operates drive amplifier number 1, the voltage regulator, and the overcurrent protection circuit. The function of R21 is to assure positive starting of the oscillator.

Design Criteria

The following assumptions and guide lines were used in the study of the frequency reference oscillator.

- a. The oscillator receives power from a 20 volt tap such that the output frequency is proportional to the voltage of the main d-c input bus.

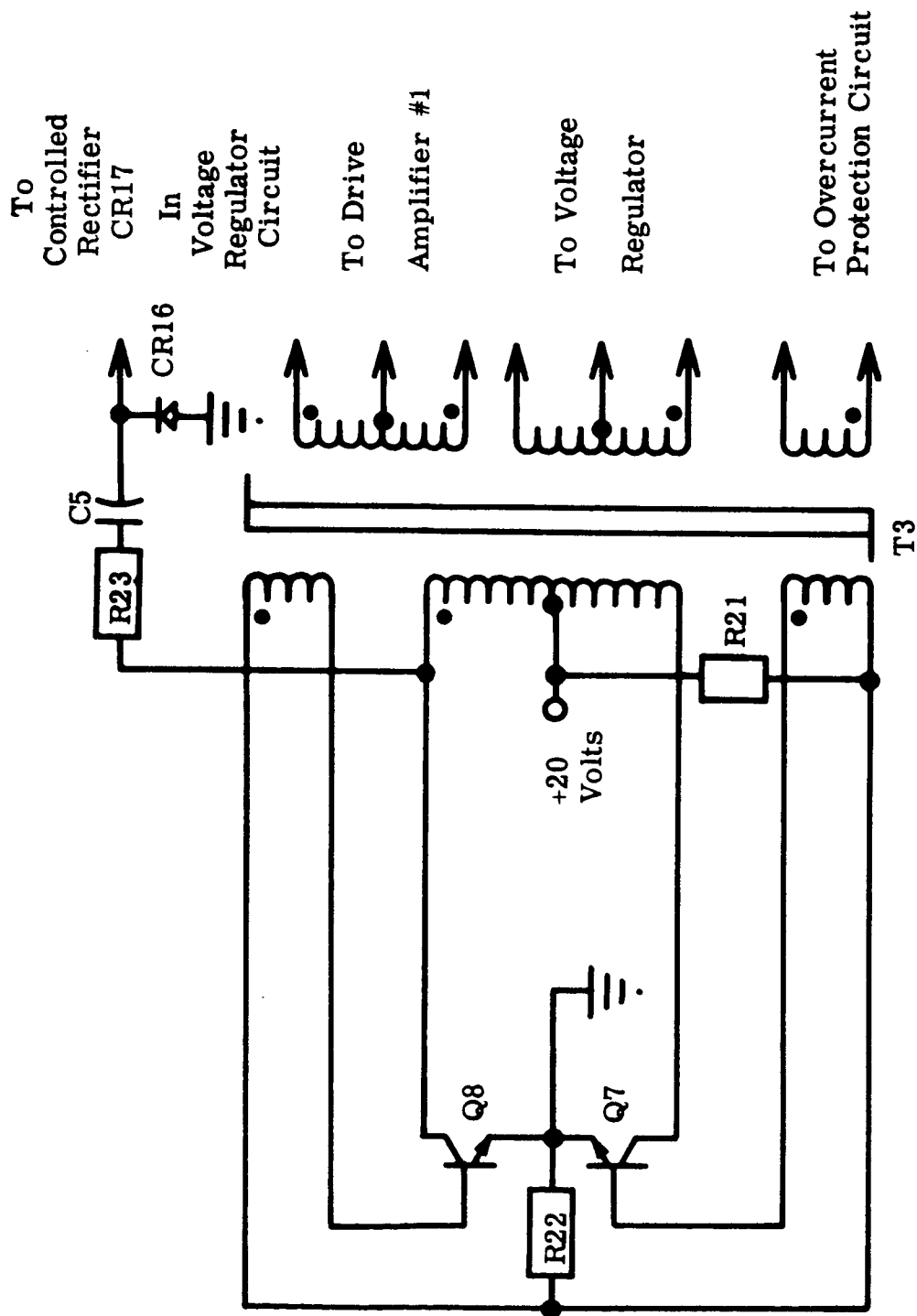


FIGURE 16

Frequency-Reference Oscillator Schematic Circuit, Task A and Task B

- b. The transformer uses Orthonol toroidal cores, and all semiconductor devices are silicon.
- c. Only readily available parts are considered.

Conceptual Data

Table 16 shows the electrical losses for the frequency reference oscillators for Task A and B at a frequency of 1000 cycles per second. This frequency was selected as a starting point for the power circuit evaluations for the converters of Task A and Task B. Oscillator power loss data at 200 cycles per second for Task B and a frequency scan to 3200 cycles per second for Task A are not presented because compared with the tabulated data the differences are insignificant. Since the frequency oscillator represents a very small portion of the total weight and losses of the converter, the additional calculations are not justified. The power losses for the auxiliary circuit are included in the voltage regulator section of this report.

Analysis and Conclusions

The frequency reference oscillator is physically small and has relatively low power losses. Since the electrical components weigh only a few ounces, the oscillator weight is expected to be only a minor factor in an optimum power conversion system.

No particular problems are anticipated with this functional block. Suitable materials and components are now available, and the design techniques have been fully verified.

7. Voltage Regulator

A voltage regulator assures a converter output voltage that remains constant within $\pm 5\%$. In this study it has been assumed that the load resistance remains constant. However, changes in nuclear-reactor source voltage without the regulator would reflect similar variations in the converter output voltage. It has been assumed that changes in the nuclear-reactor output will cause source open circuit voltage variations of $\pm 10\%$.

Description and Operation

The voltage control circuit proposed in this study, shown in Figure 17, employs pulse-width modulation. The converter output voltage is compared to a zener diode reference with the resulting difference

TABLE 16

**FREQUENCY REFERENCE OSCILLATOR POWER LOSSES
FOR 30-KW CONVERTER, TASK A AND TASK B**

COMPONENT	QUANTITY	WATTS LOSS TASK A	@ 1000 CPS TASK B
Transistors	2	0.26	0.26
Resistors	2	0.15	0.15
Transformer	1	1.0	1.0
Total Losses		1.41	1.41

**FREQUENCY REFERENCE OSCILLATOR POWER LOSSES
FOR 3.25-MW CONVERTER SYSTEM**

	WATTS LOSS TASK A	@ 1000 CPS TASK B
Total Losses	143.8	143.8

NOTE: The losses for the auxiliary circuit (R23, C5 and CR16), shown in Figure 16, are presented in the voltage regulator section. The total losses for the 3.25-mw converter system are the results of 102 electrically isolated 30-kw converters.

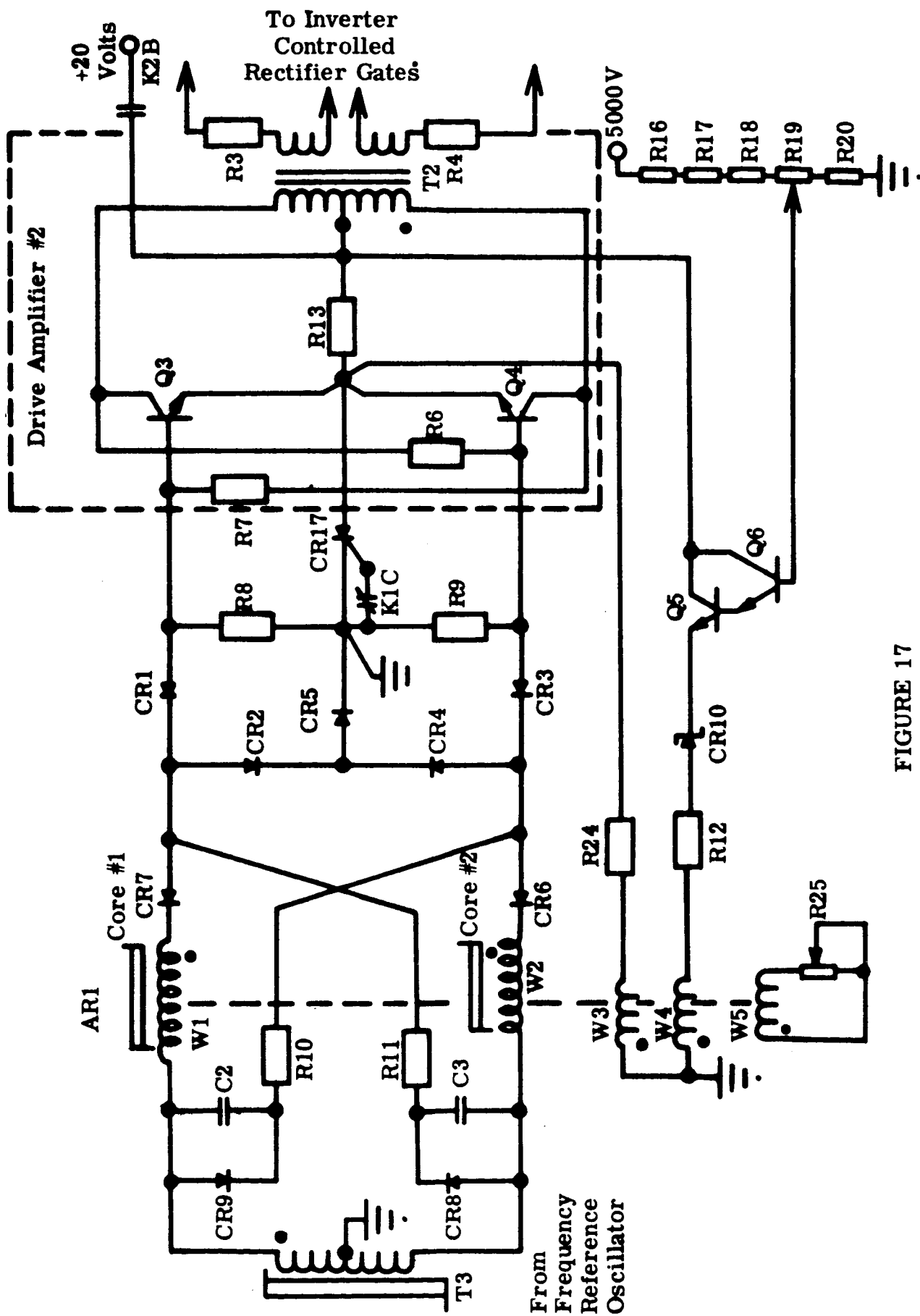


FIGURE 17
Voltage Regulator Schematic Circuit, Task A and Task B

signal controlling a magnetic amplifier switching circuit. The magnetic amplifier provides a phase-delayed, square wave signal to drive amplifier number 2. Drive amplifier number 1 operates in phase with the frequency reference, independent of the voltage regulator, and controls the gating of a pair of inverter controlled rectifiers. The second pair of inverter controlled rectifiers is gated by drive amplifier number 2, controlled by the voltage regulator.

The operating power for the voltage circuit is from an isolated 20 volt control bus from the nuclear-thermionic source. The sensing signal is obtained from a resistor voltage divider network connected to the 5000 volt d-c converter output terminals.

Detailed operation of the voltage control circuit, shown in Figure 17, is described below. Assume that the output voltage of T3 is positive (all polarities are taken with respect to the dot) and that controlled rectifier CR17 and transistor Q3 are in conduction. Therefore, K1C is opened and the output voltage of T2 is positive. Voltage at the positive terminal of T2 drives current through R7, CR1, CR2 and CR5 to ground, maintaining positive bias on the base of Q3 by virtue of the three diode-voltage drops. Magnetic core number 2 of amplifier AR1 is saturated during this part of circuit operation, allowing current conduction through R9, CR3, CR6, and winding W2 from T3. The voltage drop across R9 provides negative bias on the base of Q4 with respect to its emitter, thus holding Q4 non-conducting. This operating state exists until the polarity of T3 reverses.

When the output voltage of T3 becomes negative, current flows from T3 through CR8, R11, CR2 and CR5 to ground. With CR2 and CR5 conducting, a positive voltage is applied to the magnetic amplifier winding W1 through CR7. Only exciting current flows in W1 until saturation occurs. No significant change in the bias condition on Q3 or Q4 takes place before magnetic amplifier core number 1 saturates. Negative bias is maintained on Q4 through the voltage divider, R6 and R9, since the circuit is designed so that the voltage drop across CR17 is greater than that across R9. Therefore, a time delay takes place after the voltage of T3 reverses before there is any change in the voltage of T2.

Once saturation takes place in core number 1 of AR1, current flows from ground through R8, CR1, CR7, winding W1 to T3. The voltage drop across R8 applies a negative bias to the base of Q3, turning Q3 off. Interruption of current in T2 is accompanied by a reversal of voltage across its inductive windings. Current now flows through R6 and the parallel combination of R9 and

CR3, CR4 and CR5 to ground, resulting in a positive bias on Q4 turning it on. Positive bias is maintained on the base of Q4 by the voltage divider R6 and R9. The polarity of T2 remains negative until T3 reverses and core number 1 of magnetic amplifier AR1 again saturates, causing Q3 and Q4 to switch to their original states.

Magnetic amplifier winding W4 operates from the voltage sensing circuit through a zener diode voltage reference CR10. The function of this winding is to reset the iron cores of the magnetic amplifier after saturation. The degree to which the cores are reset determines the time required for saturation and thus controls the conduction angle of the inverter controlled rectifiers, i. e., the pulse-width.

The converter output voltage is sensed through Q6, amplified by Q5 and compared to the reference voltage drop of CR10. An increase in converter output voltage causes an increase in reset voltage on W4 which increases the time required to saturate the magnetic amplifier, reducing the pulse-width of the inverter voltage and thus decreasing the converter output voltage level. The converse is true if the output voltage decreases.

The converter is started by closing a relay K2 which closes the contact K2B between the 20 volt control bus, the frequency reference oscillator, and the magnetic amplifier winding W3. At this time only the frequency oscillator and winding W3 are energized. When the generator circuit breaker K1 is energized, applying voltage to the inverter circuit, contact K1C across the gate to cathode of CR17 is opened. The control rectifier CR17 is then turned on by the auxiliary circuit from the frequency reference oscillator. With CR17 conducting, the circuit to ground is completed for drive amplifiers No. 1 and 2 and winding W3 is removed from service. The function of W3 is to cause the magnetic amplifier cores to be fully reset prior to applying voltage to the inverter circuit. This assures that the drive amplifiers will begin operation in the correct mode.

Winding W5 connected through the parasitic load R25 determines the response time of the magnetic amplifier. The rate of converter voltage build-up may be changed by adjusting the value of R25. It may be desirable to build up at a slow rate and later increase the speed of response of the voltage control. This may be accomplished by changing R25 from a low value at start-up to a high value during normal operation.

If for any reason the magnetic amplifier cores should fail to saturate, the normal turn-off signal will not be available to Q3 or Q4. In the absence of control signals, the drive amplifier would act as a free-running oscillator, running at a lower than normal frequency out of synchronism with the frequency reference. To prevent this situation, capacitors C2 and C3 are used. Assume that the voltage of T3 has been positive and now reverses. A current pulse will be driven through R9, CR3, R10, C2 by the negative voltage change on T3. The voltage drop across R9 will bias Q4 negatively, causing it to turn off. This assures reversal of the voltage of T2 in the manner previously described. Such a current pulse occurs each time T3 reverses polarity, even though normal magnetic amplifier saturation has taken place. Of course, had Q4 been turned off normally, the subsequent pulse would have no effect.

Gate-current limiting resistors R3 and R4 are included as part of drive amplifier number 2.

Design Criteria

The following assumptions and guide lines were used in the study of the voltage regulator.

- a. The regulator receives power from an isolated 20 volt control bus.
- b. The saturable reactors of the magnetic amplifiers use Orthonol toroidal cores and all semiconductor devices are silicon.
- c. Only readily available parts are considered.

Conceptual Data

The electrical power losses determined for the voltage regulator for Tasks A and B are shown in Table 17 for a frequency of 1000 cycles per second. This frequency was selected as a reasonable starting point for the power circuit evaluations for the converters of Task A and Task B. Voltage regulator power loss data for a frequency scan to 3200 cycles per second for Task A and at 200 cycles per second for Task B are not provided because only insignificant differences exist compared with the tabulated data.

TABLE 17

VOLTAGE REGULATOR POWER LOSSES FOR 30-KW
CONVERTER, TASK A AND TASK B

COMPONENT	QUANTITY	WATTS LOSS TASK A	@ 1000 CPS TASK B
Transistors	2	Nil	Nil
Resistors	13	2.1	2.1
Diodes	11	1.0	1.0
Capacitors	3	Nil	Nil
Controlled Rectifier	1	1.0	9.0
Magnetic Amplifier	1	1.0	1.0
Total Losses		5.1	13.1

VOLTAGE REGULATOR POWER LOSSES FOR 3.25-MW
CONVERTER SYSTEM

	WATTS LOSS TASK A	@ 1000 CPS TASK B
Total Losses	570.2	1336.2

NOTE: The losses for drive amplifier number 2 (R3, R4, R6, R7, Q3, Q4 and T2), shown in Figure 17, are presented in the drive amplifier section. The total losses for the 3.25-mw converter system are the results of 102 electrically isolated 30-kw converters.

Analysis and Conclusions

The voltage regulator design is straightforward. The electrical components are physically small and light weight with low losses. The losses will vary only slightly with operating frequency and can be neglected without affecting the system analysis.

No particular problems are anticipated with the voltage regulator. Suitable materials and components are now available and the design techniques have been verified.

8. Drive Amplifier

The drive amplifiers which provide square wave gating signals for the controlled rectifiers of the inverter operate in response to the frequency reference oscillator. Two such amplifiers in the inverter provide pulse-width voltage control. One amplifier operates in phase with the frequency reference oscillator and gates one set or pair of controlled rectifiers. The second amplifier gates the other set of controlled rectifiers in response to a signal which is phase-shifted with respect to the reference frequency oscillator by means of the voltage regulator. The phase-shift results in pulse-width voltage control of the inverter circuit and therefore the d-c to d-c converter.

The preceding section discusses one of the two drive amplifiers in conjunction with the voltage regulator. The other drive amplifier, identified as amplifier number 1, is a simple two-transistor circuit driven directly by the frequency-reference oscillator.

Description and Operation

Operating from a 20 volt control bus, the drive amplifiers provide square wave output voltages to the inverter controlled rectifiers. The drive amplifiers use silicon transistors as switches.

Figure 18 shows the circuit for drive amplifier number 1. A square wave signal supplied by the frequency-reference oscillator alternately turns Q1 and Q2 on and off resulting in a square wave output voltage. Like drive amplifier number 2, this amplifier is not permitted to operate until CR17 in the voltage regulator circuit is turned on by the frequency-reference oscillator. Gate-current limiting resistors R1 and R2 are included as part of the drive amplifier.



73

Design Criteria

Transistor drive amplifiers, more easily controlled than silicon controlled rectifier amplifiers and capable of operating at higher temperatures thus simplifying the cooling problem, are used exclusively.

The following assumptions and guide lines were used in the study of the drive amplifiers.

- a. The amplifiers receive power from an isolated 20 volt control bus.
- b. The transformer magnetic cores use silicon steel and all semiconductor devices are silicon.
- c. Only readily available parts are considered.

Conceptual Data

The electrical power losses determined for the drive amplifiers for Tasks A and B are presented in Table 18, for a frequency of 1000 cycles per second. As described in the frequency reference oscillator and voltage regulator sections, 1000 cycles per second was selected as the evaluation frequency to coincide with the initial value used for the converter power circuits. Presentation of power loss data at 200 cycles per second for Task B and up to 3200 cycles per second for Task A is not warranted since only insignificant differences exist compared with the tabulated data.

Analysis and Conclusions

The drive amplifiers, like the frequency-reference oscillator, are physically small and have relatively low power losses. Although the power loss for the drive amplifiers of Task B is a number of times greater than for Task A, the respective losses are a small part of the total converter losses. The drive amplifier circuits, as with the frequency-reference oscillator, are no particular problem since the design technique is straightforward and materials and components are currently available.

TABLE 18

DRIVE AMPLIFIER POWER LOSSES FOR 30-KW CONVERTER,
TASK A AND TASK B

COMPONENT	QUANTITY	AMPLIFIER #1	
		WATTS LOSS TASK A	@ 1000 CPS TASK B
Transistors	2	0.26	8.7
Resistors	3	4.5	63.9
Transformer	1	1.13	5.8
Total Losses		5.89	78.4

COMPONENT	QUANTITY	AMPLIFIER #2	
		WATTS LOSS TASK A	@ 1000 CPS TASK B
Transistors	2	0.2	12.8
Resistors	5	5.6	92.1
Transformer	1	1.16	6.0
Total Losses		6.96	110.9

DRIVE AMPLIFIER POWER LOSSES FOR 3.25-MW
CONVERTER SYSTEM

	AMPLIFIER #1	
	WATTS LOSS TASK A	@ 1000 CPS TASK B
Total Losses	600.8	7,997

	AMPLIFIER #2	
	WATTS LOSS TASK A	@ 1000 CPS TASK B
Total Losses	709.9	11,312

NOTE: The total losses for the 3.25-mw converter system are the results of 102 electrically isolated 30-kw converters.

9. Overcurrent Protection

The overcurrent protection circuit limits the steady state power converter load current to 1.25 per unit under short-circuit and provides the signal to interrupt the circuit between the generator and the converter thus protecting the inverter switching elements and rectifier diodes from the high internal temperatures generated by prolonged overload currents. Any increase in current capacity beyond one per unit results in significantly increased weight in the power inverter commutating components. The value of 1.25 per unit was chosen as a reasonable compromise between light weight and reliable operation. Moreover, it is difficult to reliably sense currents less than 1.25 per unit. The current protection circuit would be likely to cause false shutdown.

Description

The overcurrent protection circuit consists of a saturable reactor current transducer with associated rectifiers and resistor load operating into the voltage regulator. The transducer provides the input to the protection circuit; the output goes to the voltage regulator and the generator contactor.

Operation

The schematic circuit for overcurrent protection is shown in Figure 19. The transducer AR2, excited by the frequency reference oscillator, operates as a current transformer, producing a square wave current output.⁴ This square wave current is rectified and produces a voltage drop across R14 and R15 which is proportional to the converter load current. The filter capacitor C4 prevents false operation by suppressing transients.

The overcurrent protection circuit is coupled to the voltage regulator sensing circuit through diode CR11. The normal full-load converter current provides a voltage output slightly lower than that at the zener diode CR10, maintaining CR11 in a blocking state. Sufficient increase in converter output current raises the signal level so that CR11 conducts and overrides the effect of the voltage regulator sensing circuit, causing two reactions. First, the voltage regulator reduces the inverter controlled rectifier conduction

⁴ Milnes, A. G., Transducers and Magnetic Amplifiers, MacMillan & Co., Ltd., London, 1957, p. 7-10.

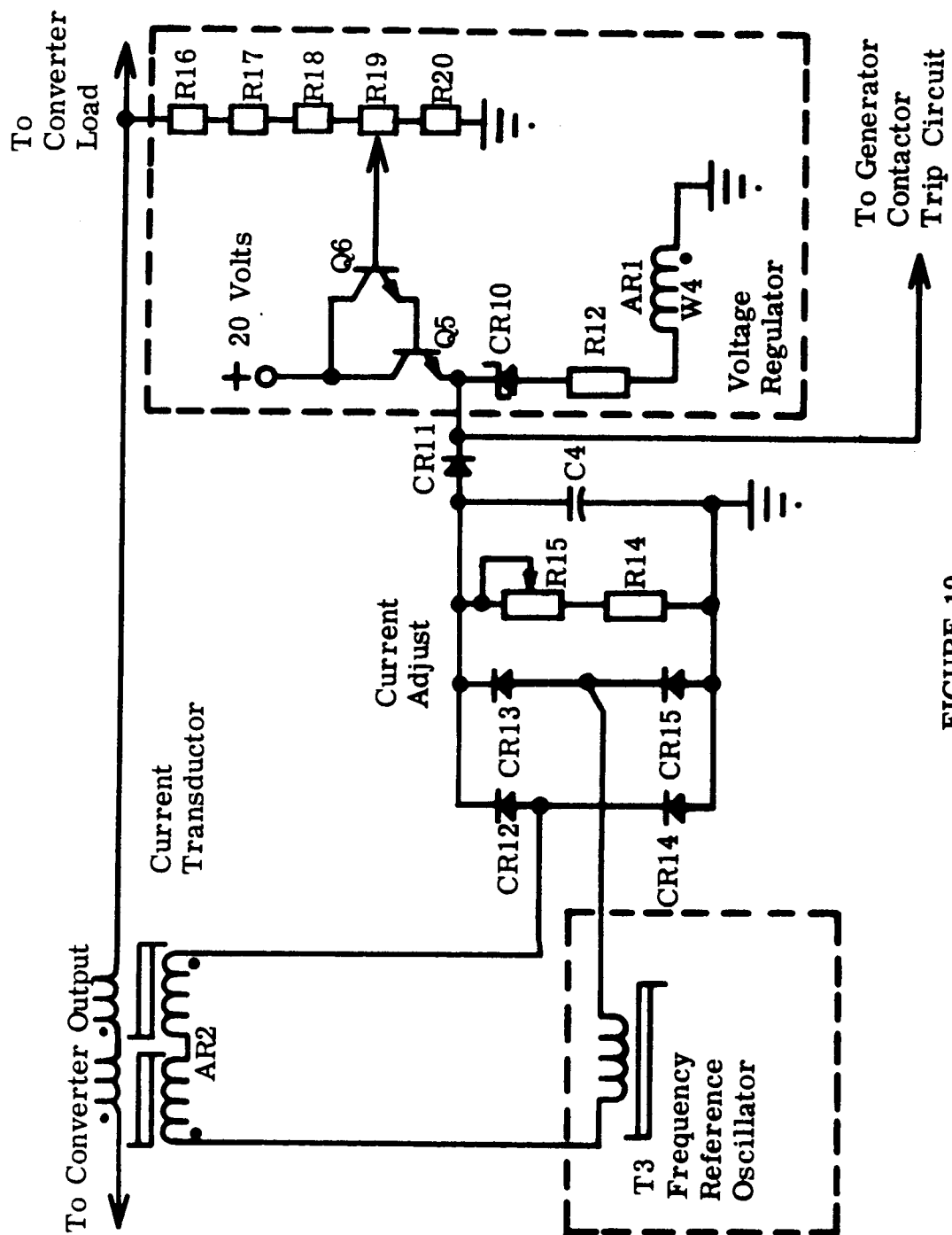


FIGURE 19

Overcurrent Protection Schematic Circuit, Task A and Task B

angle and thus prevents further rise in load current. Second, a signal is applied to the generator contactor trip circuit.

Design Criteria

The principal design criterion for the overcurrent protection circuit is that it function quickly and accurately since the power inverters are not designed to withstand prolonged overloads of more than 1.25 per unit current. The circuit chosen is capable of action within a few milliseconds.

The following additional assumptions and guide lines were used in the study of the overcurrent protection circuit.

- a. The transducer uses Orthonol toroidal cores and all semiconductor devices are silicon.
- b. Only readily available parts are considered.

Conceptual Data

As with the preceding control circuits of the frequency reference oscillator, voltage regulator and drive amplifier (and for the same reasons as presented in their discussions), the electrical losses for the overcurrent protection circuit were determined for a frequency of 1000 cycles per second only. Table 19 shows these data.

Problem Areas

It may be difficult to start the converters under load because of the fast response of the current protection circuit. At start up, the inrush current may trip the protection circuit unless the transient suppression capacitor C4 or some additional time delay is incorporated to prevent a false shutdown. During the start up period, the inverter circuit must be capable of commutating more than the 1.25 per unit load current. This type problem requires laboratory investigation on comparable, functioning converter models.

Analysis and Conclusions

Except for the frequency reference oscillator, the overcurrent protection circuit dissipates the least amount of electrical loss of all the converter functional circuits. No problems are anticipated with this functional block excluding the potential problem presented above. Suitable materials and components are currently available and the design techniques are known.

TABLE 19

OVERCURRENT PROTECTION CIRCUIT POWER LOSSES
FOR 30-KW CONVERTER, TASK A AND TASK B

COMPONENT	QUANTITY	WATTS LOSS @ 1000 CPS	
		TASK A	TASK B
Transductor	1	1.0	1.0
Resistors	2	0.63	0.63
Diodes	5	0.5	0.5
Capacitor	1	Nil	Nil
Total Losses		2.13	2.13

OVERCURRENT PROTECTION CIRCUIT POWER LOSSES
FOR 3.25-MW CONVERTER SYSTEM

	WATTS LOSS @ 1000 CPS	
	TASK A	TASK B
Total Losses	217.3	217.3

NOTE: The total losses for the 3.25-mw converter system are the results of 102 electrically isolated 30-kw converters.

B. MECHANICAL DESIGN OF TASK A CONVERTER

To obtain a lower structural weight, the individual converter functional circuits are grouped for packaging. (See also Section II. D.). The grouping is dictated by the maximum allowable component temperatures of each functional block. Those components requiring the same coolant temperature use the same coolant circuit. Only two different cooling system temperatures are required for the Task A converters, one in series through packages 1 and 2 and a separate, higher temperature system for package 3.

Figure 20 shows the coolant flow to the separate converter functional circuit packages. The input filter and power rectifier share one common package and coolant circuit.

The voltage regulator, frequency-reference oscillator, drive amplifier, and overcurrent protection circuit share a second common package and coolant circuit. The inverter switching circuit and output filter capacitors have about the same maximum allowable temperature as the components in this second package and are included in it. However, they require a coolant inlet temperature about 20°C below that of the other functional circuits; therefore they use a separate cold plate. The transformer and output filter inductor make up the third group, sharing a common package and coolant circuit.

1. Functional Block Package Number 1

This package contains the input filter and the rectifier assembly. A separate rectifier package structure would require about 40% of the total package weight compared to 20% for the present arrangement. Detail design features and conceptual data of the input filter and rectifier assembly differ somewhat; therefore they are described separately below.

Input Filter

Mechanical Design Description

The cylindrical ML capacitors of the input filter are flange-mounted to support rails which are parallel to the capacitor centerlines. Cylindrical fuses are clip-mounted to the rails, using adhesive bonding to reduce thermal resistance across the mechanical joints. Filter losses are comparatively low, and the capacitor surface area encourages cooling by direct radiation provided that a compartment wall temperature is maintained at approximately 100°C. However, since such a mounting location is not provided,

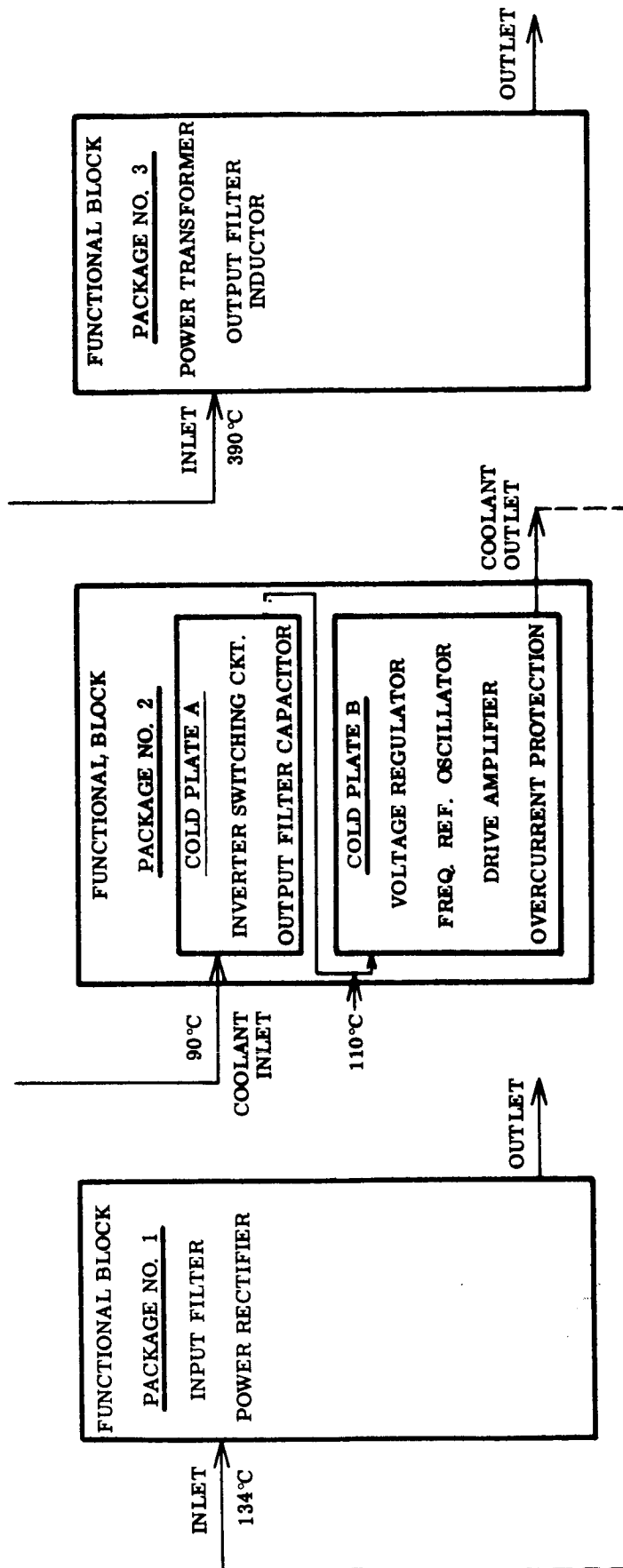


FIGURE 20

Block Diagram of Mechanical Conceptual Design For D-C To D-C Converter, Task A

coolant conduits are included, integral with the support rails, with cooling by direct conduction from the capacitor case to the coolant fluid.

Design Criteria

In addition to the information presented in the conceptual mechanical design discussion, (Section II), the following specific design criteria were used to calculate the input filter data.

- a. Maximum capacitor operating temperature is 180°C for all designs. This is approximately equivalent to 25% derating of the rated allowable temperatures. The coolant conduit wall temperature is 140°C .
- b. Weight of the cooling system and supporting structures is 20% of the total weight.

Conceptual Data

In the summary (part 4, page 91) of this section, Tables 20 through 22 present packaged input filter weights, volumes, and electric power losses compared to inverter switching frequencies of 1000 to 3200 cycles per second. The input filter weights given in Table 20 consider the electrical components, structure, and cooling tube system. The weight and volume are constant over the specified frequency spectrum while the power losses increase with frequency to a maximum of 13.4 watts at 3200 cycles per second. The input filter-power rectifier package has a coolant temperature of 134°C on the basis of electrical losses at an inverter frequency of 2300 cycles per second.

Rectifier

Mechanical Design Description

A typical cold plate mechanical arrangement is shown in Figure 21. The diodes are stud-mounted to beryllium oxide insulation, which is bonded to the cold plate of the liquid metal coolant system by adhesive bonding to reduce the thermal resistance across the joints. In addition, the insulation is mechanically fastened to the cold plate to insure a safe, reliable mechanical assembly. Capacitors used in conjunction with the silicon diodes are contained in insulated cases and are mounted directly to the cold plate adjacent to the diodes.

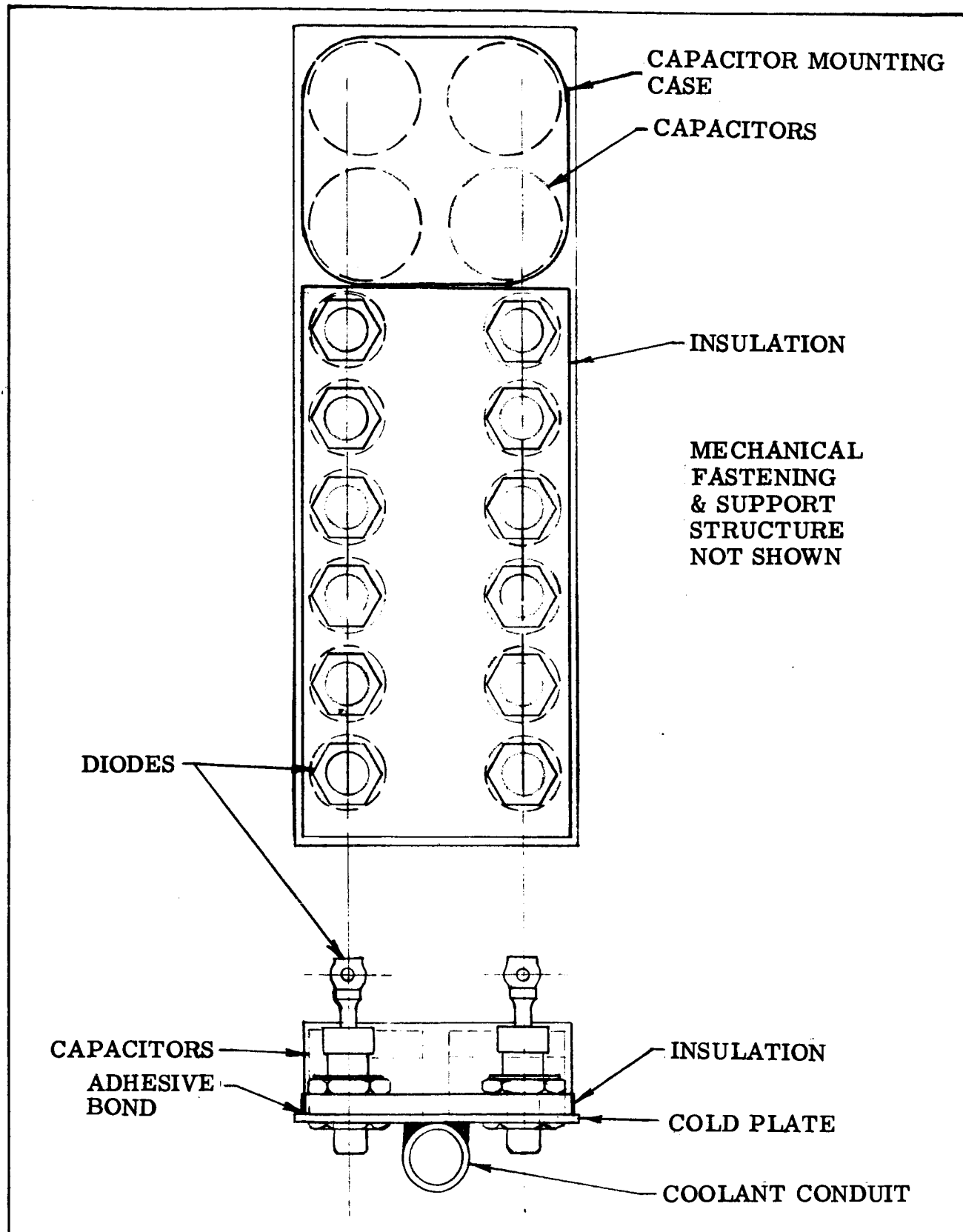


FIGURE 21

Typical Arrangement of Rectifier Assembly, Task A

Beryllium oxide insulation is used to provide both required dielectric strength and a good thermal path to conduct heat from the diodes to the cold plate. Thus, the insulation thickness is dictated by thermal conduction requirements rather than dielectric requirements. The insulation is segmented every four or five inches to provide lower weight and relief from thermal stresses because of adhesive bonding.

The diodes are mounted to the cold plate in 4 rows of six diodes each. Each two rows of diodes are cooled by one parallel coolant duct.

Design Criteria

In addition to the design criteria presented in the conceptual mechanical design discussion, the following information was used to calculate the data for the rectifier assembly.

- a. The semiconductor diode junction temperature is 150°C . This is equivalent to 25 percent derating of the diode junction temperature.
- b. Supporting structure weight is 20 percent of the total weight, exclusive of the cold plate, insulation, and coolant tubing weight.

Conceptual Data

In the summary (part 4, p. 91) of this section, Tables 20 through 22 present packaged rectifier assembly weights, volumes, and power losses compared with inverter switching frequencies. In Table 20 showing the electrical component, structure, and cooling tube system weight of the rectifier assembly, the weight remains constant over the frequency range of 1000 to 3200 cycles per second. The packaged volume also remains constant while the power losses increase with increasing frequency.

Problem Areas

Problem areas which appear to be common to all the functional blocks of this study except the transformer and output filter inductor are as follows.

- a. Effort must be made to develop reliable techniques for forming and joining beryllium to other metals which might be used in a complete power system cooling loop.

- b. Development of reliable adhesive bonds is required for use in a space environment. Such bonds should be either sufficiently elastic to relieve thermal expansion differentials or strong enough to resist thermal stresses created between materials of different relative expansions.

2. Functional Block Package Number 2

Mechanical Design Description

The inverter switching circuit, output filter capacitor, voltage regulator, frequency-reference oscillator, overcurrent protection circuit, and drive amplifier have about the same maximum allowable temperature and are contained in this package. The inverter switching circuit components and output filter capacitors share one cold plate, while the remaining four functional block circuits share a second cold plate. Separate cold plates are used because the inverter electrical parts and filter capacitors require a coolant inlet temperature about 20°C below that of the other components. If each of the separate converter circuits was packaged individually, the structure would require from 32 to 40% of the total weight, instead of 28% as assumed for this common package. The inverter switching circuit semiconductors are adhesive-bonded to beryllium oxide insulation which is adhesive bonded to the cold plate. This is similar to the rectifier assembly construction depicted in Figure 21. Mechanical fastening is used in conjunction with bonding to insure reliable construction.

As in the rectifier assembly, the beryllium oxide insulation provides required dielectric strength and also a good thermal path to conduct heat from the components to the cold plate. Thermal conduction requirements dictate the insulation thickness under the silicon controlled rectifiers and commutating diodes where sufficient cross-sectional area of insulation is required to transfer heat laterally from the semiconductors to the coolant tubes with low temperature drop. Elsewhere, where needed, insulation thickness is assumed to be 0.040 inches. This choice is based on mechanical strength and handling requirements.

The inverter components are arranged in two modules for each 30-kw converter and mounted in rows to the cold plate. Output filter capacitors are clip-mounted to the same cold plate with adhesive bonding used between capacitors, clips, and cold plate to reduce thermal resistance. Potting may also be used to aid in cooling. Each row of components is cooled by two coolant ducts parallel to the row.

The voltage regulator, frequency-reference oscillator, drive amplifier, and overcurrent protection circuit share a second cold plate in this package. A typical mechanical arrangement is shown in Figure 22. The transformers and some resistors are mounted directly to the cold plate with smaller components mounted on aluminum or beryllium printed circuit boards. All components are adhesive bonded as well as mechanically fastened to facilitate heat flow. A controlled rectifier in the voltage regulator is mounted through beryllium oxide insulation to the cold plate, similar to the component mounting described above for the inverter switching circuit. Transformers are potted to facilitate cooling. Printed circuit boards are insulated by fluidizing or use of a similar coating or by use of beryllium oxide sheet.

Design Criteria

In addition to the design criteria listed in the conceptual mechanical design discussion, (Section II), the following information was used to calculate the data.

- a. In the inverter switching circuits, semiconductor junction temperatures are 150°C for diodes and 112°C for silicon controlled rectifiers, equivalent to 25% derating. Case and stud temperatures are dictated by the thermal resistance and losses for each particular component.
- b. The output filter capacitor case temperature is 100°C .
- c. For the voltage regulator, frequency-reference oscillator, drive amplifier, and overcurrent protection circuit, semiconductor stud or case temperatures are 140°C . This is equivalent to at least 25% derating of the device junction temperatures.
- d. Supporting structure weight is 28 percent of the total weight. This is exclusive of the cold plate, insulation, and coolant tubing weight.

Conceptual Data

The packaged weights, volumes, and power losses for all the functional blocks of this group are shown in Tables 20 through 22 in the summary (part 4, p. 91) of this section. The stated parameters have been compared to an inverter switching frequency of 1000 through 3200 cycles per second. The filter capacitor weight, volume, and losses have been included in the total output

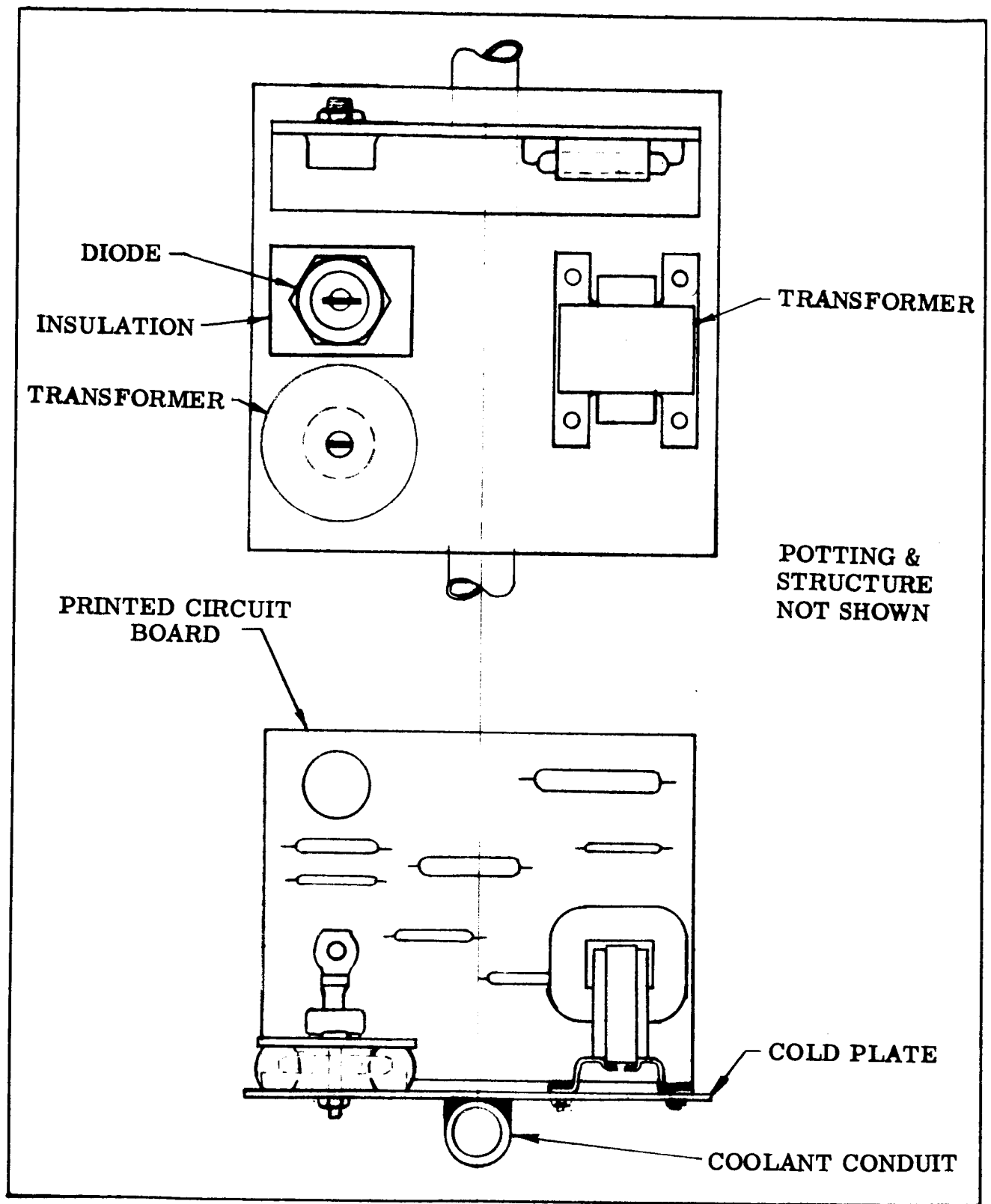


FIGURE 22

Typical Assembly Arrangement of Control Circuit Components, Task A

filter. Therefore, the filter values shown include the inductor contained in Package Number 3. Table 20 presents the weight of the different functional blocks considering the electrical components, structure, and cooling duct system. Table 21 shows that the inverter circuit packaged volume remains constant while the output filter volume decreases with increasing frequency. Table 22 shows that the inverter and output filter make up a major percentage of the converter losses. It is seen that the inverter losses increase with frequency while the output filter losses decrease with increased frequency. Weight, volume, and losses of the remaining functional blocks of this package are constant over the inverter frequency range.

The coolant inlet temperature for the inverter circuit and the output filter capacitors is 90°C with a coolant inlet temperature of 110°C for the remaining functional block components sharing this package. The coolant temperatures are based on electrical power losses at an inverter frequency of 2300 cycles per second.

3. Functional Block Package Number 3

Mechanical Design Description

The output filter inductor and the power transformers share the third common package and circuit. The power transformer assembly consists of two identical 15 kva transformers, one for each inverter module.

The output filter consists of capacitors with a maximum operating temperature of 125°C and an inductor with a maximum internal temperature of 550°C. The capacitors are included in Package Number 2 while the inductors are included in this package with the power transformers.

Transformer and inductor cores are mounted directly to structural rails for support. A typical cold plate and mechanical construction for the transformer are shown in Figure 23. Cooling straps and coolant conduits are integral parts of the structure supporting the cores. The inductors and transformers are potted to facilitate removal of heat by conduction to the coolant conduits.

Design Criteria

The following specific design criteria are used to calculate the required conceptual data for the transformer-inductor package.

- a. The maximum transformer and inductor internal hot spot temperatures are assumed to be 550°C. Internal temperature rise is assumed to be 150°C.

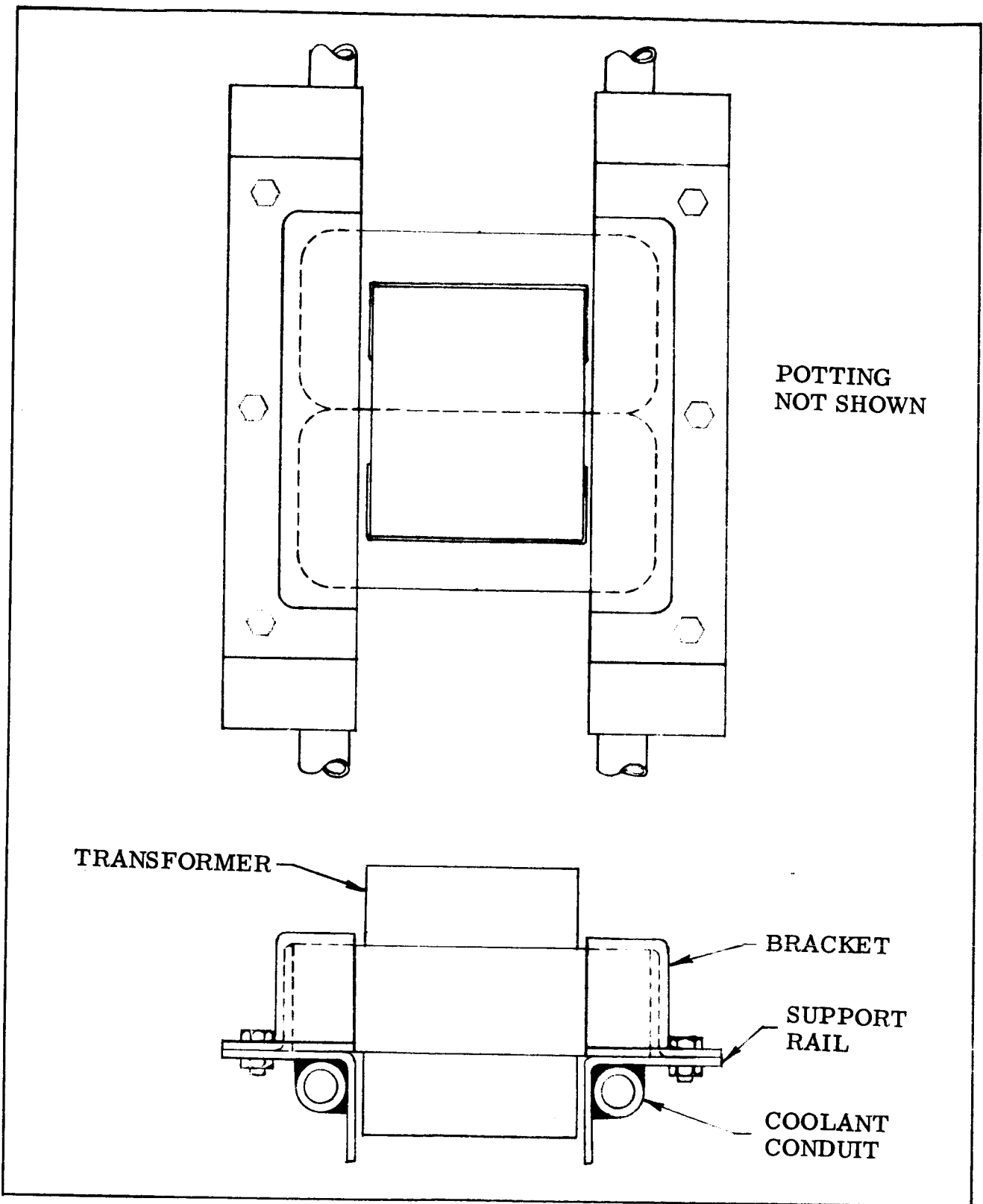


FIGURE 23

Typical Assembly Arrangement of Transformer, Task A

- b. Total package weight including insulation, structure, and cooling provisions is assumed to be 1.9 times the transformer and inductor electromagnetic weight.

Conceptual Data

The weights, volumes, and losses of the power transformer and output filter inductor compared to inverter frequencies of 1000 to 3200 cycles per second are given in Tables 20 through 22 in part 4 of this section. The inductor weight, volume, and losses are included with the capacitor of Package Number 2 and presented as the total output filter. Table 20 shows the weight of the functional block components, the structure, and the cooling duct system. From the tables, it is seen that the transformer has the desirable characteristics of decreasing weight, volume, and losses with increased inverter frequency.

The coolant inlet temperature for the transformer-inductor package is 390°C for power losses at an inverter frequency of 2300 cycles per second.

Problem Areas

The problem areas common to all the converter transformers and output filter inductors of this study are as follows.

- a. The most difficult problem anticipated is the development of high reliability, long service life transformers, and inductors at temperatures in the order of 550 to 600°C. There is little previous experience to draw upon.
- b. If transformers and inductors are to be potted to aid cooling, considerable development is needed to obtain potting compounds that are applicable to high temperatures and a space environment.
- c. Care must be taken in choice and use of materials to avoid severe thermal stresses at design temperature extremes.
- d. If the potting of transformers proves unfeasible for use in the design temperature range, an alternate design must be developed such as routing of coolant tubes directly through the magnetic core devices.

4. Converter Data and Summary of Results

Results of weight, volume, and losses are presented in Tables 20 through 22 for the Task A 30-kw converter. Data are presented for 102 electrically isolated 30-kw converters for the total system of 3.25 megawatts. Tabulated results for inverter switching frequencies of 1000, 1800, 2000, 2200, and 3200 cycles per second are calculated. Data at 2300 cycles per second were extrapolated. The tabulated weights and volumes for the different functional circuits have been proportioned to their respective total packaged weights and volumes. The weights listed in Table 20 include the electrical components, structure, and cooling system.

Table 23 and Figure 24 are used to select a minimum weight converter system for Task A. Table 23 shows the weights of a 30-kw converter considering the nuclear-thermionic source and thermal radiator weight penalties because of converter power losses. The source weight penalty was assumed to be 10 pounds per kilowatt of loss. The radiator weight penalties were determined from Figure 5.

The curve of Figure 24, prepared from the data of Table 23, flattens to a minimum converter system weight of 218 pounds from 2200 to 2300 cycles per second. For purposes of this study, 2300 cycles per second have been selected as the frequency which will result in minimum system weight. The specific weight of the converter system for Task A, which includes the thermal radiator and nuclear-thermionic source weight penalties, is 7.27 pounds per kilowatt. Excluding penalties, the converter specific weight for Task A is 5.84 pounds per kilowatt.

The converter efficiency at 2300 cycles per second, based on the losses presented in Table 22, is 93.4%.

TABLE 20
WEIGHT DATA FOR 30-KW CONVERTER, TASK A

Inverter Circuit Frequency (cps)	1000	1800	2000	2200	2300	3200
Functional Blocks						
Input Filter (lb)	67.5	67.5	67.5	67.5	67.5	67.5
Inverter Switching Circuit	33.3	33.3	33.3	33.3	33.3	33.3
Transformer	59.5	48.7	47.0	45.5	44.8	40.7
Rectifier Assembly	2.3	2.3	2.3	2.3	2.3	2.3
Output Filter	45.6	28.1	26.2	24.3	23.8	20.1
Frequency Reference Oscillator	0.3	0.3	0.3	0.3	0.3	0.3
Voltage Regulator	2.1	2.1	2.1	2.1	2.1	2.1
Drive Amplifier	0.6	0.6	0.6	0.6	0.6	0.6
Overcurrent Protection	0.6	0.6	0.6	0.6	0.6	0.6
Total Weight (lb)	211.8	183.5	179.9	176.5	175.3	167.5

WEIGHTS FOR 3.25-MW CONVERTER SYSTEM

Total Weight (lb)	21,600	18,700	18,350	18,000	17,900	17,100
-------------------	--------	--------	--------	--------	--------	--------

NOTE: Functional circuit weights are proportional to respective total packaged weights. Given weights include electrical components, structure, and cooling system. The totals for the 3.25-mw converter system are the results of 102 electrically isolated 30-kw converters.

TABLE 21
VOLUME DATA FOR 30-KW CONVERTER, TASK A

Inverter Circuit Frequency (cps)	1000	1800	2000	2200	2300	3200
Functional Blocks						
Input Filter (ft. ³)	1.35	1.35	1.35	1.35	1.35	1.35
Inverter Switching Circuit	0.75	0.75	0.75	0.75	0.75	0.75
Transformer	0.30	0.25	0.24	0.23	0.23	0.21
Rectifier Assembly	0.05	0.05	0.05	0.05	0.05	0.05
Output Filter	0.24	0.15	0.14	0.13	0.13	0.12
Frequency Reference Oscillator	0.01	0.01	0.01	0.01	0.01	0.01
Voltage Regulator	0.03	0.03	0.03	0.03	0.03	0.03
Drive Amplifier	0.04	0.04	0.04	0.04	0.04	0.04
Overcurrent Protection	0.01	0.01	0.01	0.01	0.01	0.01
Total Volume (ft. ³)	2.78	2.64	2.62	2.60	2.60	2.57

VOLUME DATA FOR 3.25-MW CONVERTER SYSTEM

Total Volume (ft. ³)	284	269	267	265	265	262
----------------------------------	-----	-----	-----	-----	-----	-----

NOTE: Functional circuit volumes are proportional to respective total packaged volumes. The totals for the 3.25-mw converter system are the results of 102 electrically isolated 30-kw converters.

TABLE 22
POWER LOSS DATA FOR 30-KW CONVERTER, TASK A

Inverter Circuit Frequency (cps)	1000	1800	2000	2200	2300	3200
Functional Blocks						
Input Filter (watts)	5.0	9.2	10.0	10.8	11.0	13.4
Inverter Switching Circuit	923.4	1004.1	1024.5	1044.9	1055	1145.7
Transformer	740.0	634.0	624.0	606.0	598	560.0
Rectifier Assembly	74.9	82.8	85	86.9	88	97.0
Output Filter	476.0	360.9	346	329.1	322	291.6
Frequency Reference Oscillator	1.4	1.4	1.4	1.4	1.4	1.4
Voltage Regulator	5.1	5.1	5.1	5.1	5.1	5.1
Drive Amplifier	12.9	12.9	12.9	12.9	12.9	12.9
Overcurrent Protection	2.1	2.1	2.1	2.1	2.1	2.1
Total Losses (watts)	2240.8	2112.5	2111.0	2099.2	2095.5	2129.2

POWER LOSS DATA FOR 3.25-MW CONVERTER SYSTEM

Total Losses (kw)	229.2	215	215	214	213.9	217
-------------------	-------	-----	-----	-----	-------	-----

NOTE: The totals for the 3.25-mw converter system are the results of 102 electrically isolated 30-kw converters.

TABLE 23

WEIGHTS WITH SOURCE AND RADIATOR PENALTIES FOR 30-KW CONVERTER, TASK A

Inverter Circuit Frequency (cps)	1000	1800	2000	2200	2300	3200
Functional Blocks						
Input Filter (lb.)	67.6	67.6	67.6	67.7	67.7	67.7
Inverter Switching Circuit	52.6	57.4	59.0	61.7	63.0	82.2
Transformer	67.9	55.9	54.1	52.4	51.8	47.0
Rectifier Assembly	3.9	4.0	4.1	4.1	4.2	4.3
Output Filter	51.0	32.2	30.1	28.0	27.2	23.4
Frequency Reference Oscillator	0.4	0.4	0.4	0.4	0.4	0.4
Voltage Regulator	2.4	2.4	2.4	2.4	2.4	2.4
Drive Amplifier	0.9	0.9	0.9	0.9	0.9	0.9
Overcurrent Protection	0.7	0.7	0.7	0.7	0.7	0.7
Total Converter Weight Including Thermal Radiator and Source Weight Penalties (lb)	247.4	221.5	219.3	218.3	218.3	229.0

WEIGHTS WITH SOURCE AND RADIATOR PENALTIES FOR 3.25-MW CONVERTER SYSTEM

Total Converter Weight Including Thermal Radiator and Source Weight Penalties (lb)	25,250	22,600	22,400	22,267	22,267	23,350
--	--------	--------	--------	--------	--------	--------

NOTE: The totals for the 3.25-mw converter system are the results of 102 electrically isolated 30-kw converters.

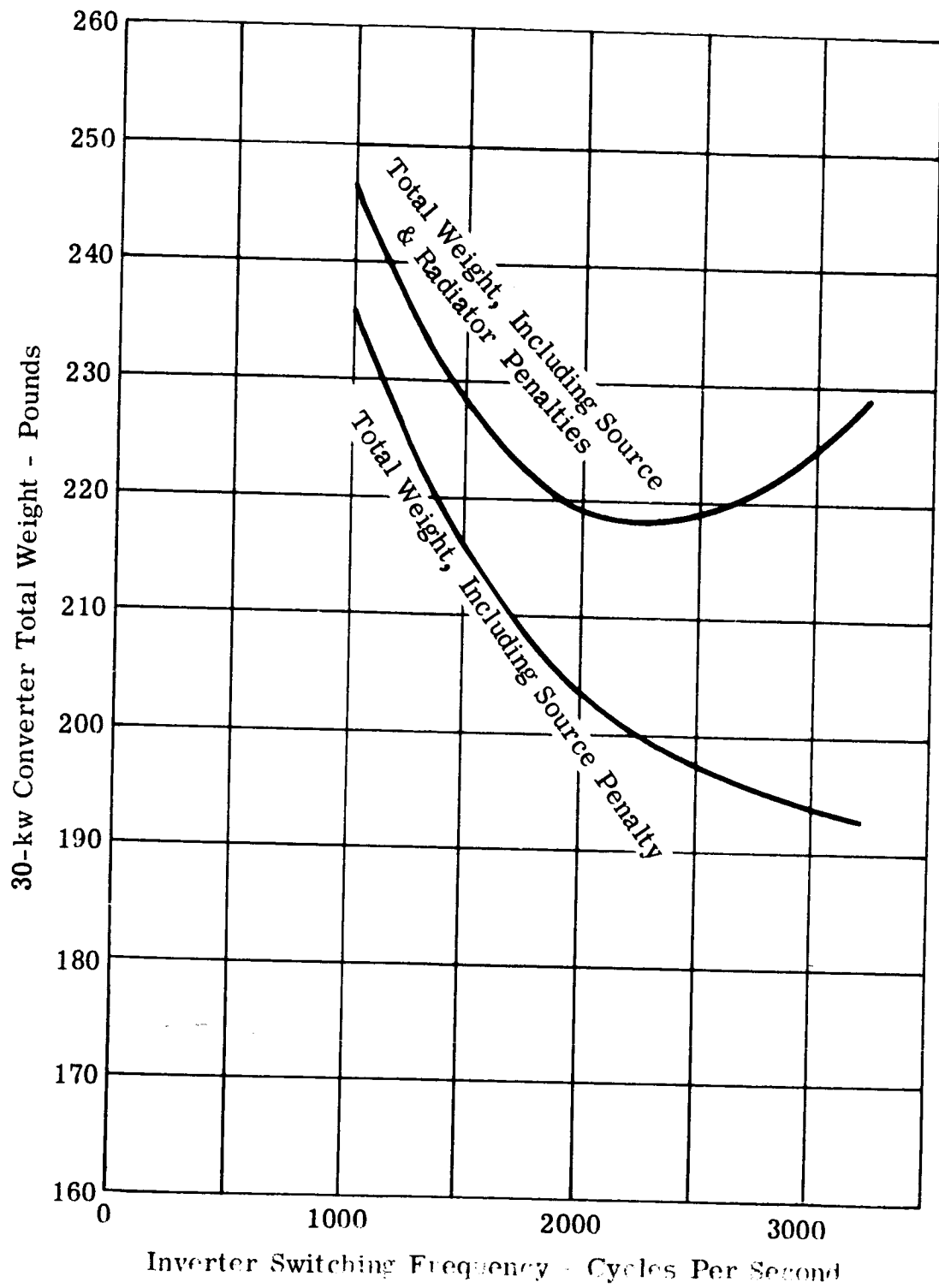


FIGURE 24

30-kw Converter Total Weight Vs. Inverter Switching Frequency,
Task A

C. MECHANICAL DESIGN OF TASK B CONVERTER

The individual functional blocks of the Task B converter are contained in four common packages. As described in the discussion for the Task A converters, this type grouping provides lower structural weight than is possible with packaging each functional circuit separately. Choice in grouping is dictated by the maximum allowable temperature of each functional block. Those having the same coolant temperature share the same coolant circuit. The functional blocks for Task B are grouped as follows.

The input filter is contained in a separate package because of the low coolant temperature required by the electrolytic capacitors. The voltage regulator, frequency-reference oscillator, drive amplifier, and overcurrent protection circuit share a common package and cooling circuit. The inverter circuit capacitors and output filter capacitors are included in this package, but use separate cold plates because of slightly different required coolant inlet temperatures. The transformer, inverter commutating inductor, and output filter inductor make up another group, sharing a common package and coolant circuit. The gas tube rectifiers and inverter circuit thyratrons and commutating diodes make up the last group, sharing a common package and coolant circuit. Figure 25 is a block diagram depicting the four packages and showing coolant flow to them.

Only two different coolant inlet temperatures are required for the Task B converters. A low temperature coolant system is in series through Package Numbers 4 and 5, and a separate high temperature system is in series through Package Numbers 6 and 7.

The general design criteria and problem areas for the Task B converters are the same as described for the converters of Task A and as presented in Section II D, Mechanical Design Description.

1. Functional Block Package Numbers 4, 5, 6 and 7

Functional Block Package Number 4

The input filter is contained in this separate package with a coolant inlet temperature of 43°C. The use of electrolytic capacitors with a maximum operating temperature of 65°C dictates the need for such a low coolant inlet temperature which is dangerously close to the freezing point of eutectic NaK. An alternate design using ML capacitors would allow a coolant inlet temperature as high as 130°C. However, it would require a device weight of 628 pounds, compared to 14 pounds for the electrolytic capacitors.

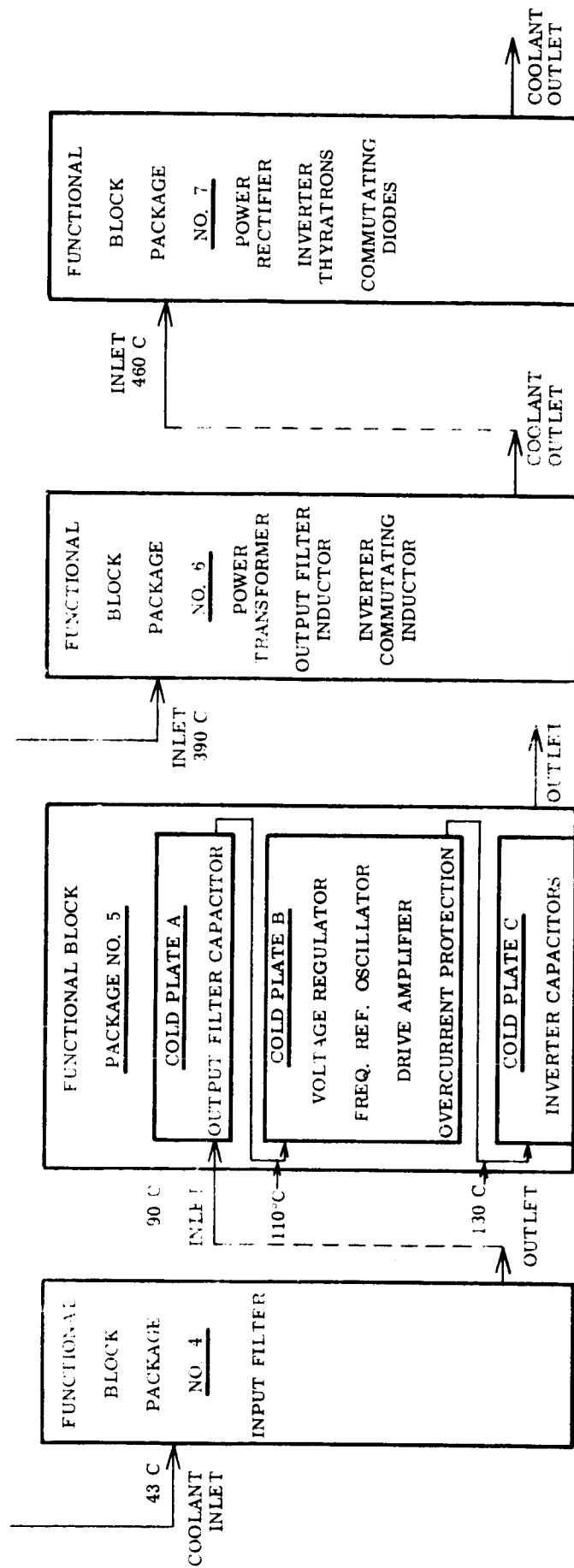


FIGURE 25

Block Diagram Of Mechanical Conceptual Design For I-5 To D-C Converter, Task B

The cylindrical capacitors are flange mounted to support rails parallel to the capacitor centerlines. Adhesive bonding is used to reduce thermal resistance across the mechanical joints.

The following specific design criteria were used to calculate the input filter data. This is in addition to the guide lines presented in the Task A conceptual mechanical design discussion.

- a. Maximum capacitor operating temperature is 65°C. This is approximately equivalent to 25% derating of the rated allowable temperature. The coolant conduit wall temperature is 45°C.
- b. Weight of the cooling system and supporting structures is 37.5% of the total weight.

Functional Block Package Number 5

The voltage regulator, frequency-reference oscillator, overcurrent protection circuit, and drive amplifier have the same maximum allowable temperature and are grouped in this common package, sharing a common cold plate. The inverter circuit commutating capacitors and output filter capacitors are mounted on separate cold plates and are included in this package. Separate cold plates are used because the output filter capacitors require a coolant inlet temperature about 20°C below that for a common cold plate whereas the inverter capacitors can withstand about 20°C above that of the common cold plate temperature.

Mechanical construction and cooling means are the same as discussed for the Task A Functional Block Package Number 2 design. In addition to the design criteria listed for the Task A converter mechanical design discussion, the following specific assumptions and guide lines were used to calculate data.

- a. Inverter circuit commutating capacitors have a maximum operating temperature of 180°C. This is approximately equivalent to a 25% derating of the rated allowable temperature. The coolant conduit wall temperature is 140°C.
- b. Supporting structure weight is 20% of the total weight. This is exclusive of the weight of cold plate, insulation, and coolant tubing.

Functional Block Package Number 6

The output filter inductor, inverter commutating inductors, and power transformer share this common package and coolant circuit. The mechanical construction, cooling means, and design criteria are the same as for the Task A converter Functional Block Package Number 3.

Functional Block Package Number 7

The gas tube rectifiers, inverter circuit thyratrons, and commutating diodes are included in this common package and share a common coolant circuit. The rectifier assembly gas tube diodes have an allowable maximum anode temperature of 800°C, whereas the inverter thyratrons and diodes are limited to 600°C at the grid and anode, respectively. To simplify packaging, all three component types are mounted on a common coolant circuit with a 600°C device limit.

The tubes are flange mounted directly to a cold plate that has integral coolant ducts routed adjacent to them. The devices are cooled directly by conduction through the columbium flanges to the cold plate. The flanges are adhesive bonded to the plate to reduce thermal resistance across the joint and are mechanically fastened to insure structural reliability. The cold plate and cooling tubes are of columbium.

In addition to the design criteria presented in the Task A converter conceptual design discussion, the following information was used to calculate data.

- a. Gas and vapor tube devices are assumed to have an allowable envelope temperature of 600°C, equivalent to the allowable grid and anode temperature. The coolant conduit wall temperature is 475°C.
- b. Total package weight, including insulation, coolant tubes, and structure, was assumed to be 3.8 times the total device weight.

Conceptual Data

Weights, volumes, and power losses of the individual functional blocks for the Task B 30-kw converter and for the 3.25 megawatt converter system are given in Table 24 at an inverter frequency of 200 cycles per second.

Converter weights are presented with source and thermal radiator weight penalties and with penalties excluded. The weight penalties were obtained as described for the converters of Task A. The specific weight of the converter system for Task B, which includes the thermal radiator and nuclear-thermionic source weight penalties, is 30.9 pounds per kilowatt. Excluding penalties, the converter specific weight for Task B is 28.8 pounds per kilowatt.

The converter efficiency is 86.4%.

D. COMPARISON OF TASK A AND TASK B CONVERTERS

To determine which of the two converter configurations studied will be used for the remaining program tasks described in the Introduction of this report, a direct comparison of the Task A and Task B converter data is presented. The results of converter weight, volume, and power loss provided under separate discussions in the mechanical design portion of this section of the report are presented in Table 25. An item not considered in the previous tabulations is source over capacity penalty. As discussed under Conceptual Design, Section II of this report, a 25% penalty is required in thermionic source capacity for the Task B converter because of the voltage limitation on the inverter vapor tube thyatron and the specified nominal source operating voltage. As a result, the packaged Task B 30-kw converter weight, including prior penalties, is increased by 75 pounds to a total of 1001 pounds.

To select the converter configuration for further program study, minimum converter system weight was established as the criterion. On this basis, it becomes necessary to enlarge our concept of the converter system and consider its implementation in a space vehicle. Several additional factors which require investigation regarding their effect on system weight are nuclear-radiation shielding, transmission line requirements between the nuclear-thermionic source and the converter and the load, and the transmission line cooling requirements.

Considering the above factors, the following assumptions were used to calculate data for the Task A and Task B converter systems.

TABLE 24

**WEIGHTS, VOLUMES, AND POWER LOSSES FOR 30-KW
CONVERTER SYSTEM, TASK B**

	*Packaged Wt. (lb)	+Packaged Wt. & Penalties (lb)	Volume (ft. ³)	Losses (watts)
Inverter Circuit Frequency	200 Cycles Per Second			
Functional Blocks				
Input Filter	22.4	25.2	0.36	40
Inverter Switching Circuit	521.3	545.9	8.33	1814
Transformer	121.1	131.7	0.62	938
Rectifier Assembly	15.2	23	0.82	712
Output Filter	176.3	188	1.08	1031.1
Frequency-Reference Oscillator	0.4	0.4	0.01	1.4
Voltage Regulator	2.0	2.4	0.03	13.1
Drive Amplifier	4.5	8.8	0.15	189.3
Overcurrent Protection	0.6	0.7	0.01	2.1
Total	863.8	926.1	11.41	4741

**WEIGHTS, VOLUMES, AND LOSSES FOR 3.25-MW
CONVERTER SYSTEM**

Total	88,100	94,500	1165	484,000
--------------	---------------	---------------	-------------	----------------

*Converter weight includes electrical components, structure, and cooling system.

+Converter weight plus thermal radiator and source weight penalties.

NOTE: The totals for the 3.25-mw converter system are the results of 102 electrically isolated 30-kw converters.

TABLE 25

COMPARATIVE DATA FOR 30-KW CONVERTERS, TASK A AND TASK B

	CONVERTER OF TASK A				CONVERTER OF TASK B			
	*Packaged Wt. (lb)	+Packaged Wt. and Penalties (lb)	Vol. (ft. 3)	Losses (watts)	*Packaged Wt. (lb)	+Packaged Wt. and Penalties (lb)	Vol. (ft. 3)	Losses (watts)
Frequency:	2300 Cycles Per Second				200 Cycles Per Second			
Functional Blocks								
Input Filter	67.5	67.7	1.35	11	22.4	25.2	0.36	40
Inverter Switching Circuit	33.3	63.0	0.75	1055	521.3	545.9	8.33	1814
Transformer	44.8	51.8	0.23	598	121.1	131.7	0.62	938
Rectifier Assembly	2.3	4.2	0.05	98	15.2	23	0.82	712
Output Filter	23.8	27.2	0.13	322	176.3	188	1.08	1031.1
Frequency Reference Oscillator	00.3	0.4	0.01	1.4	0.4	0.4	0.01	1.4
Voltage Regulator	2.1	2.4	0.03	5.1	2.0	2.4	0.03	13.1
Drive Amplifier	0.6	0.9	0.04	12.9	4.5	8.8	0.15	189.3
Overcurrent Protection	0.6	0.7	0.01	2.1	0.6	0.7	0.01	2.1
Subtotal	175.3	218.3	2.60	2095.5	863.8	926.1	11.41	4741.0
Source Over Capacity Penalty		0				75		
Total	175.3	218.3	2.60	2095.5	863.8	1001.1	11.41	4741.0

COMPARATIVE DATA FOR 3.25-MW CONVERTER SYSTEM

Total	17,900	22,267	265	213,900	88,100	102,102	1,165	484,000
-------	--------	--------	-----	---------	--------	---------	-------	---------

* Converter weight includes electrical components, structure and cooling system.

+ Converter weight plus thermal radiator and source weight penalties.

NOTE: The totals for the 3.25-mw converter system are the results of 102 electrically isolated 30-kw converters.

1. The nuclear reactor was based on a 32.5-mw unit with 3.25-mwe. Dimensions were 150 centimeters in height with a 150 centimeter diameter.
2. Only the converter power circuit components (input filter, inverter, transformer, rectifier, and output filter) determined the nuclear shield requirements. The control circuits are the same for both Task A and Task B converters and therefore can be protected with a local shield which will not influence the difference-weight between systems.
3. Converter device and material radiation tolerance limits are presented in Table 26. These values, based on a level which would result in no damage, were obtained from reports prepared by Battelle Memorial Institute as documented. Either fast neutron or gamma radiation values are given in the table depending upon device susceptibility.
4. The nuclear radiation shield requirements consider fast neutron radiation only. The gamma radiation shield requirements are the same for the Task A and Task B converters; therefore, a difference in gamma shield weight does not exist.

The silicon controlled rectifier radiation tolerance of 2×10^8 N cm⁻² established the limit for the Task A converter. The electrolytic capacitor of the input filter with a radiation tolerance of 10^{15} N cm⁻² established the limit for the Task B converter. The output filter capacitor for the Task B converter was considered to be located in the vicinity of the load and therefore was not the limiting component.

5. Component radiation dosage was integrated for a period of one year.
6. Lead was used for the shield. Although fast neutrons are shielded best by lithium hydride, lead was selected to try to include effects of a gamma shield.
7. The shadow shield, located at the nuclear-thermionic source, was based on the reactor dimensions given in item 1. The shield thickness and reactor size were established using the procedures documented in TID-7004, "Reactor Shielding Design Manual," from the Naval Reactor Branch, Division of Reactor Development, March, 1956.

TABLE 26

CONVERTER COMPONENT RADIATION TOLERANCE, TASK A AND TASK B

	Task A Converter		Task B Converter	
	Component Type	Radiation Tolerance	Component Type	Radiation Tolerance
Functional Blocks				
Input Filter Capacitor	ML	$3 \times 10^{15} \text{N cm}^{-2}$	Electrolytic	10^{15}N cm^{-2}
Inverter				
Controlled-Rectifier	Silicon	$2 \times 10^8 \text{N cm}^{-2}$	Vapor Tube	$*10^{10} \text{erg g}^{-1}(\text{c})$
Feedback Diode	Silicon	$4.8 \times 10^{12} \text{N cm}^{-2}$	Gas Tube	$*10^{10} \text{erg g}^{-1}(\text{c})$
Commutating Inductor		$10^{10} \text{erg g}^{-1}(\text{c})$	High Temp. Materials	$*10^{10} \text{erg g}^{-1}(\text{c})$
Commutating Capacitor	ML	$3 \times 10^{15} \text{N cm}^{-2}$	ML	$3 \times 10^{15} \text{N cm}^{-2}$
Transformer	High Temp. Materials	$10^{10} \text{erg g}^{-1}(\text{c})$	High Temp. Materials	$10^{10} \text{erg g}^{-1}(\text{c})$
Rectifier Power Diode	Silicon	$4.8 \times 10^{12} \text{N cm}^{-2}$	Gas Tube	$*10^{10} \text{erg g}^{-1}(\text{c})$
Output Filter Inductor	High Temp. Materials	$10^{10} \text{erg g}^{-1}(\text{c})$	High Temp. Materials	$10^{10} \text{erg g}^{-1}(\text{c})$
Capacitor	Film-Paper	$2 \times 10^{13} \text{N cm}^{-2}$	Film Paper	$2 \times 10^{13} \text{N cm}^{-2}$

*Radiation tolerance based on 10^{15}nvt .

NOTE: Radiation tolerance for components is at a level which will result in no damage to devices or materials. Information was obtained from REIC Report No. 34, June 30, 1964, "Radiation - Effects State of the Art," and REIC Report No. 36, October 1, 1964, "The Effect of Nuclear Radiation on Electronic Components, Including Semiconductors," both from Information Center, Battelle Memorial Institute, Columbus 1, Ohio.

8. Weight of a total of 102 electrically isolated 30-kw converters was used.
9. The power circuits of the converters for Task B were located 2 meters (6.56 feet) and 5 meters (16.4 feet) from the source. The power circuits for the Task A converters were located 20 meters (65.6 feet) from the source. The engine loads and converter control circuits were also located 20 meters from the source.
10. The source to converter transmission line conductors were number 3 gage copper equivalent for both Task A and Task B converters.
11. Conductor losses were calculated for 900°F with $\pm 100^\circ\text{F}$ oscillations. Heat rejection was at 400°F into an external radiator for the Task A conductors. Heat rejection was at 700°F for the conductors of Task B.
12. A source weight penalty of 10 pounds per kilowatt was used for the transmission line losses.
13. Transmission line conductor coolers were spaced 1.5 feet apart, with a total of 90 per Task A converter.

The results of the Task A and Task B converter system weights are presented in Table 27. These data must be considered very preliminary because of the lack of details on a specific vehicle configuration, mission, and flight profile and because the time devoted to it was necessarily limited. However, the information does provide an insight as to what can be expected when these details are defined. The results obtained show that the two systems are comparable, with the Task B converter system offering a slight weight advantage. It is on the basis of this advantage that the NASA technical project manager selected the Task B converter components and the associated circuit configuration for the remaining program tasks.

TABLE 27

WEIGHT COMPARISON FOR 3.25-MW CONVERTER SYSTEM,
TASK A AND TASK B

	Converter System		
	Task A		Task B
Source to Converter Distance (feet)	65.6	6.56	16.4
Source to Converter Conductor	20,500	1,360	3,400
Weight with Source and Cooling Requirement Penalties (lb)			
Converter to Load Conductor	--	3,650	3,040
Weight with Source and Cooling Requirement Penalties (lb)			
Converter Weight (lb)	22,267	102,102	102,102
Shield Weight (lb)	103,500	40,700	32,500
Total Weight (lb)	146,267	147,812	141,042

SECTION I V

CONVERTER SYSTEM ANALYSIS FOR TASK C AND TASK D

CONVERTER SYSTEM ANALYSIS OF TASK C AND TASK D

A. ELECTRICAL SYSTEM

In the program study of Task C and Task D, several converters operate in parallel from a single nuclear-thermionic power source to provide a common output to a number of 30-kw electric ion engines. This approach achieves a weight advantage over the single-source, single-converter concept of Tasks A or B. This weight-saving comes about by elimination of the input filter and the reduction of output filter requirements. An even greater advantage is gained in increased power capacity at the load bus for fault clearing.

Several different methods were considered for operating converters from a common source. A primary consideration was system simplicity. In the system selected, Figure 26, the input terminals of a number of converters are connected in parallel to the nuclear-thermionic power source, while the rectifier output terminals are connected in series to a single filter network. Series connection of the converter output rectifiers assures proper load division between converters and provides an output voltage which is the sum of the individual converter voltages.

As indicated in Figure 26, some converters, though all are identical, are connected in a voltage regulating mode while others operate in a nonregulating mode. The nonregulating units operate at full output voltage under all normal conditions, whereas the regulating converters operate with a variable pulse-width in response to the output voltage magnitude.

Because the converter output voltages are rectified before being added in series, it is not necessary for the inverter stages to operate in synchronism. In fact, each inverter operates at a frequency slightly different from all others. Commutation of the controlled rectifiers of any one converter thus occurs at random with respect to the other converters. The probability of commutation occurring simultaneously in several converters is, therefore, remote. It is this concept that makes possible the elimination of the input filter in group operation of the converters.

Operation of the system can best be explained by reference to the nuclear-thermionic source volt-ampere characteristics of Figure 4. The normal source characteristic is shown by curve V_2 and the extreme characteristics by V_1 and V_3 , while the voltage required for constant output power is shown by curve V_4 . Curve P_1 is the source power output corresponding to V_1 . Since voltage regulation can reduce output voltage only, the combined group of converters will be required to give rated output when operating at point

TO NUCLEAR-THERMIONIC
SOURCE

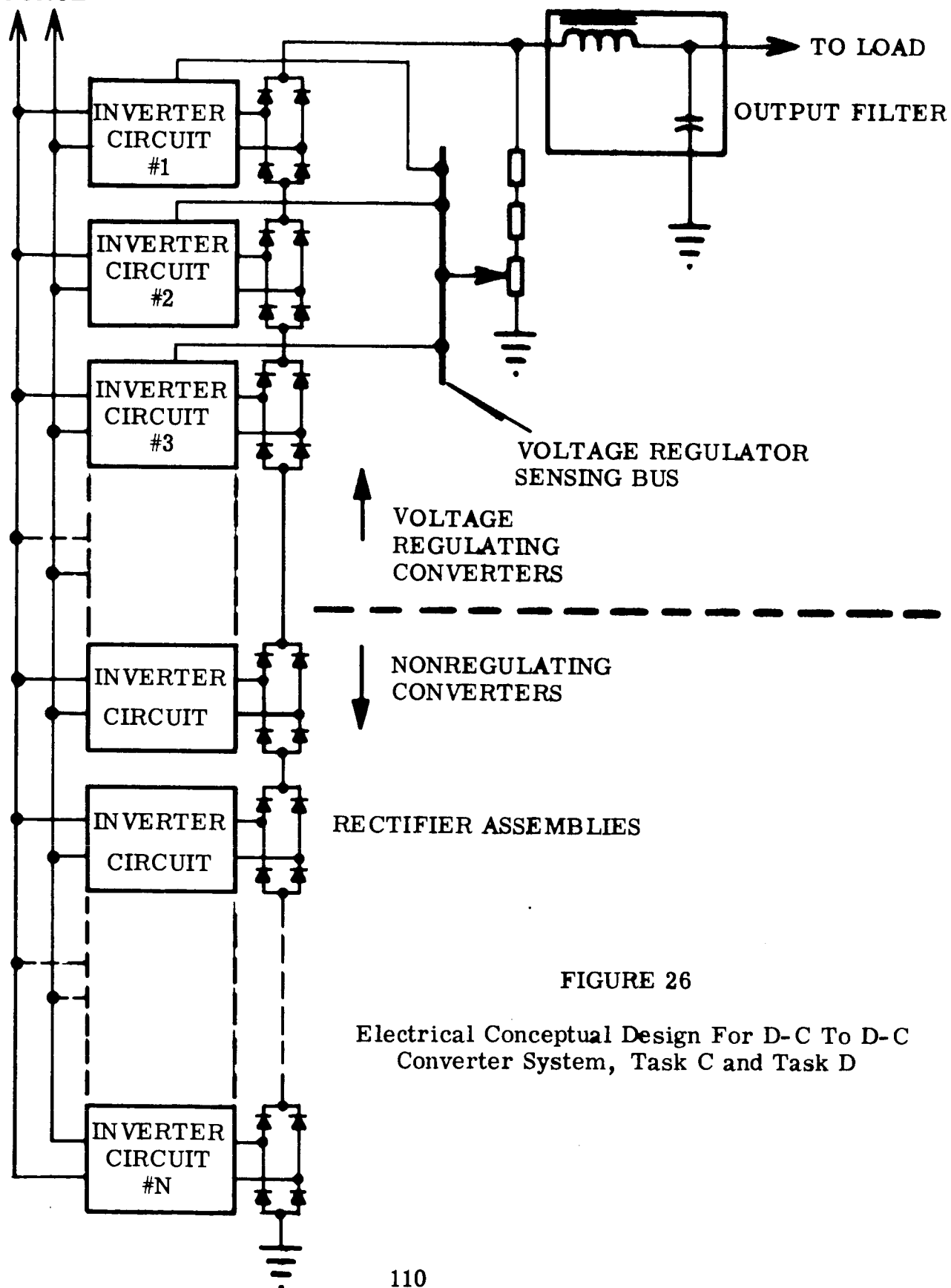


FIGURE 26

Electrical Conceptual Design For D-C To D-C
Converter System, Task C and Task D

(1). If, for example, the total number of converters in the group was 7, then each converter would supply one-seventh of the output voltage. When operating at point (3), however, the source voltage is 1.4 times that at point (1). The number of converters required to give the same output voltage as before is only five ($7/1.4 = 5$) and each converter delivers one-fifth the total power. Thus, in this particular example, voltage regulation is performed by only two converters while five, operating in a nonregulating mode, supply the output voltage proportional to the source voltage. It will be noted that the converters operate at a constant current for a constant load impedance. When the source volt-ampere characteristic is normal; i. e., V_2 , the input to the converters will be that of point (2) and the two voltage-regulating converters will operate with their controlled rectifiers phased back sufficiently to maintain constant output voltage.

The foregoing example illustrates that the total number of converters required in a single group is the ratio of the operating maximum to minimum source voltage times the number of nonregulating converters required at maximum voltage. Therefore, the voltage-regulating converters represent a penalty to the system because of the source voltage variation. The greater this variation, the greater the penalty in terms of installed converter capacity. Comparison of Figures 3 and 4 reveals that the larger the ratio of load power to the nuclear-thermionic source capacity, the greater this penalty becomes. With light weight converters, the weight penalty has only a minor effect; but with the converters employing vapor and gas tubes, the penalty is highly significant.

Figure 27 shows the relative number of converters required in a single group as a function of source utilization. The source utilization factor P/P_m is the source power supplied to the load divided by the maximum power which the source can supply at its minimum volt-ampere output characteristic (V_1 , Figure 4). The top curve of Figure 27 shows that the required total number of converters rises quite rapidly as maximum source utilization is approached.

The difference between the two curves of Figure 27 represents the installed converter capacity penalty. Obviously, the lower the source utilization the greater will be the source weight penalty of the system. The lowest-weight converter-source system will, therefore, result in a compromise between source capacity and converter capacity.

Although the components used in converter design (semiconductors vs. tubes, etc.) are the major factors determining the weight of the converter, voltage and current ratings have a direct effect. In general, low voltage and high current result in greater weight. Converters designed to operate at a high source utilization factor (P/P_m) will be heavier than similar converters (same type components) designed for operation at lower source utilization because high source utilization requires higher current-handling capability.

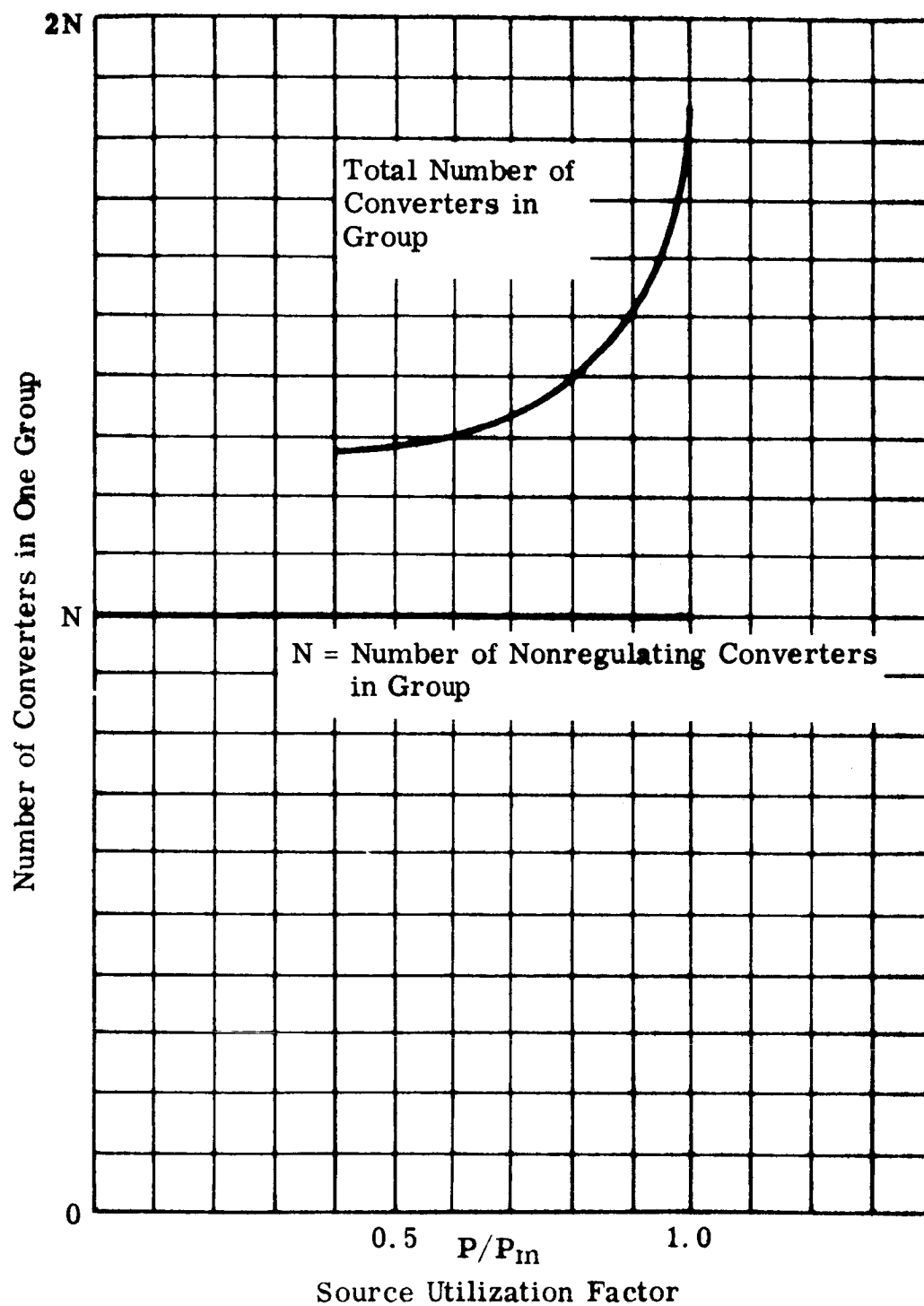


FIGURE 27

Total Number of Converters Relative to the Number of Nonregulating Converters Vs. Source Utilization Factor, Task C and Task D

Minimum system weight determines the selection of the total number of converters to operate together in a group comprising a single power channel, and the number of converters of this group to operate in a regulating mode. As previously discussed, the total weight which can be charged against the converters includes, in addition to the converter weight, a source weight penalty because of less than full source utilization. The source weight penalty will be the same for both Tasks C and D, and is assumed to be 10 pounds per kilowatt. The converter weight depends on the component design requirements and the source voltage.

1. Converter System for Task C

The converters for Task C operate from a nominal source voltage of 50 volts. Figure 28 shows the weight per kilowatt chargeable to the converters for Task C as a function of source utilization. The minimum system weight occurs at a source utilization factor, P/P_m , of approximately 0.6, with a converter plus source weight penalty of 100 pounds per kilowatt. The change in weight is less than 3% for P/P_m of 0.45 to 0.7. As shown in Figure 27, the total number of converters for this range in source utilization factor varies from $1.28N$ to $1.34N$. The possible total numbers (N) of converters that can be operated together in groups for minimum converter system weight, with a ratio of total number of converters to nonregulating converters of 1.28 to 1.34, are listed in Table 28.

The requirements of Tasks A and B imply that a system capacity with 102 channels, each of 30-kw rating, should be arranged in convenient groups for Task C and Task D. Six groups of 17 converters each fulfill this condition. This converter system configuration is selected for study in Task C. Other combinations totaling approximately 100 converters are as follows.

- a. Eleven groups of nine converters each, totaling 99 converters.
- b. Eight groups of 13 converters each or 13 groups of eight converters each, totaling 104 converters.

To serve 102 electric engines of 30-kw rating, requires 6 groups of 17 converters with each converter rated at 30-kw. Since the non-regulating units must carry the total load, these units deliver 30-kw $(17/13) = 39.2$ -kw each under normal load conditions at maximum source voltage. Although this requirement seems greater than that of the converters for Task A or Task B, it is directly comparable with exception of the 30-kva transformers, because the converters for Task A and Task B must be designed to handle both maximum

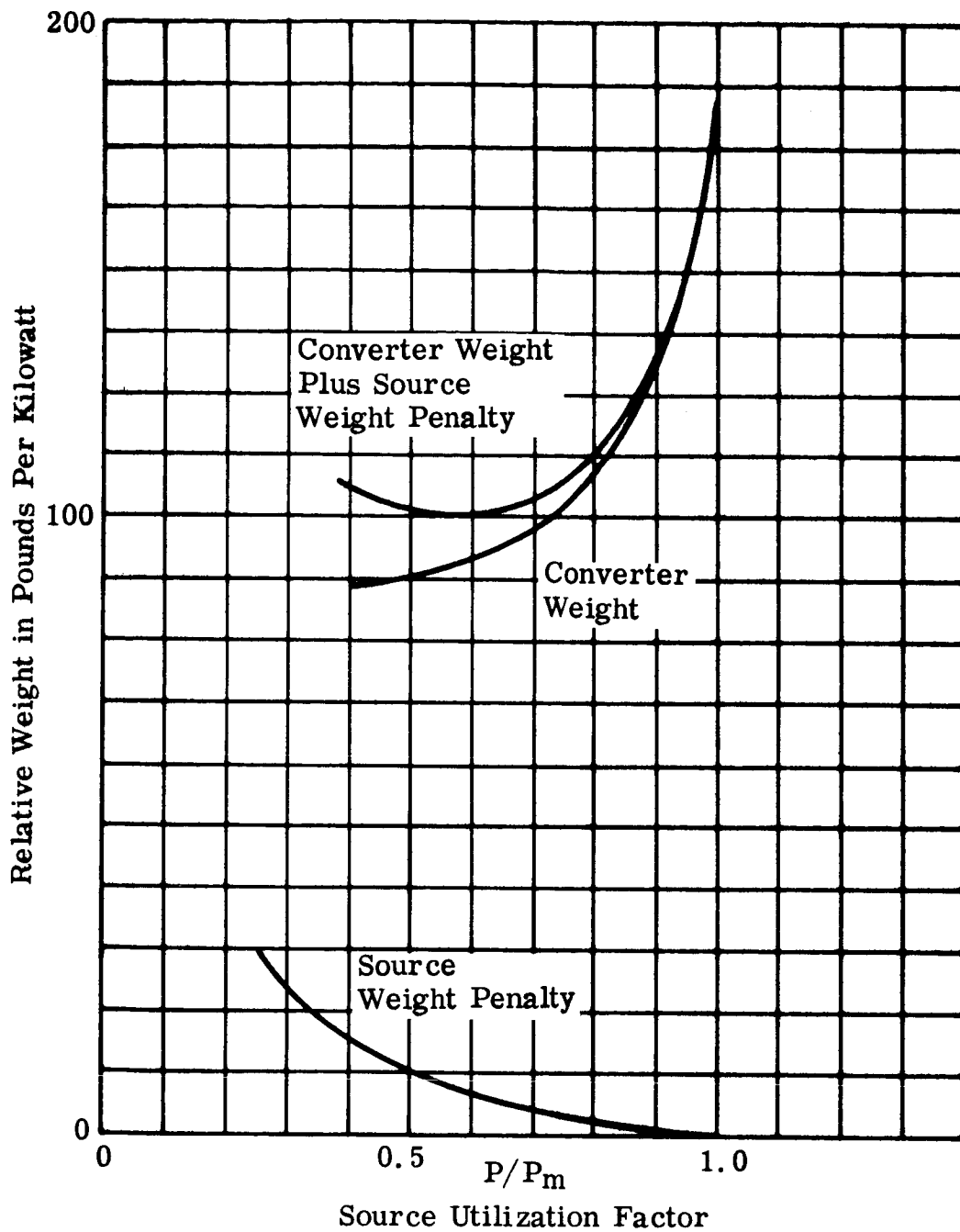


FIGURE 28
System Weight in Pounds Per Kilowatt Chargeable
to Converters as a Function of Source Utilization
Factor, Task C

TABLE 28

POSSIBLE CONVERTER SYSTEM COMBINATIONS FOR TASK C

Total No. of Converters	17	13	9	4
Nonregulating Converters	13	10	7	3
Regulating Converters	4	3	2	1
Ratio of Total to Nonregulating Converters	1.306	1.30	1.285	1.333

voltage and maximum current. The nominal power rating alone does not indicate the true requirements of the converters for Task A or Task B.

2. Converter System for Task D

The converters for Task D operate from a nominal source voltage of 100 volts. Figure 29 shows the weight per kilowatt chargeable to the converters for Task D as a function of source utilization factor, P/P_m . The minimum system weight occurs at a P/P_m ratio of approximately 0.7 where the converter plus source weight penalty is 45 pounds per kilowatt, or less than half that for Task C. The change in weight is less than 3% over a range of source utilization factors of 0.55 to 0.8. As shown in Figure 27, the total number of converters for this range in P/P_m ratio varies from 1.29N to 1.4N. The possible total numbers (N) of converters which can be grouped together for minimum system weight as a function of the total number of converters to nonregulating converters are listed in Table 29.

The same argument used in the case of Task C applies here in the selection of the number of converters to be used in each group of one power channel. Therefore, the results are likewise the same; 17 converters of 30 kilowatts each, of which 13 operate in a nonregulating mode, are selected for study in Task D. This results in a source utilization factor of 0.6 for the converter systems of Tasks C and D, which gives very nearly minimum weight.

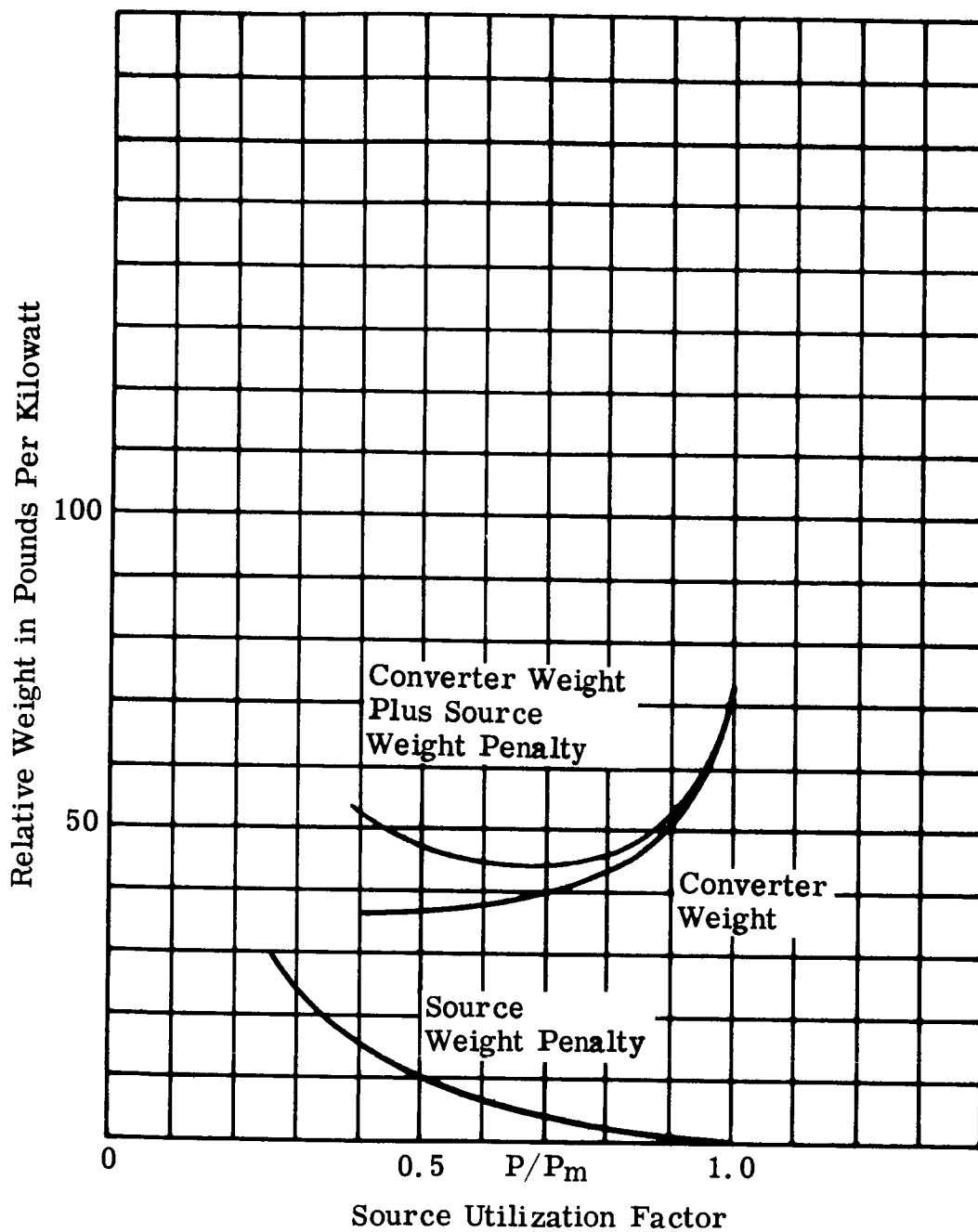


FIGURE 29

System Weight in Pounds Per Kilowatt Chargeable to
Converters as a Function of Source Utilization
Factor, Task D

TABLE 29

POSSIBLE CONVERTER SYSTEM COMBINATIONS FOR TASK D

Total No. of Converters	17	15	13	11	9	7	4
Nonregulating Converters	13	11	10	8	7	5	3
Regulating Converters	4	4	3	3	2	2	1
Ratio of Total to Nonregulating Converters	1.306	1.365	1.30	1.375	1.285	1.40	1.333

Nuclear-Thermionic Source Requirements

The selected system for both Task C and Task D consists of six isolated power channels. Each channel serves seventeen 30-kw electric ion engines for a total of 510 kilowatts.

It was determined that the source utilization factor, P/P_m , is 0.6 for the selected combination of converters. The value of P_m , for a single power channel, is then $510\text{-kw}/0.6 = 850$ kilowatts.

From the source volt-ampere curves of Figure 4, it has been determined that $P_m = (0.48 V_o)(0.55 I_s) = 0.264 V_o I_s$, where V_o is the source open-circuit voltage, and I_s is the source short-circuit current for the nominal volt-ampere curve. Since $P_m = 0.264 V_o I_s = 850$ kilowatts, $I_s = 3220/V_o$ kiloamperes. Figure 30 is included to facilitate determining the source voltage required for any value of source utilization factor. For the selected system where $P/P_m = 0.6$, the nominal source voltage $V_2 = 0.875 V_o$.

In the case of Task C, the nominal voltage is 50 volts; thus $V_o = 50/0.875 = 57$ volts. The short-circuit current of the source is then $I_s = 3220 \times 10^3/57 = 56.5$ kiloamperes for a single power channel.

For Task D, where the nominal voltage is 100 volts, $V_o = 114$ volts and $I_s = 28.25$ kiloamperes for a single power channel.

Converter efficiency has not been considered in the source capacity calculations.

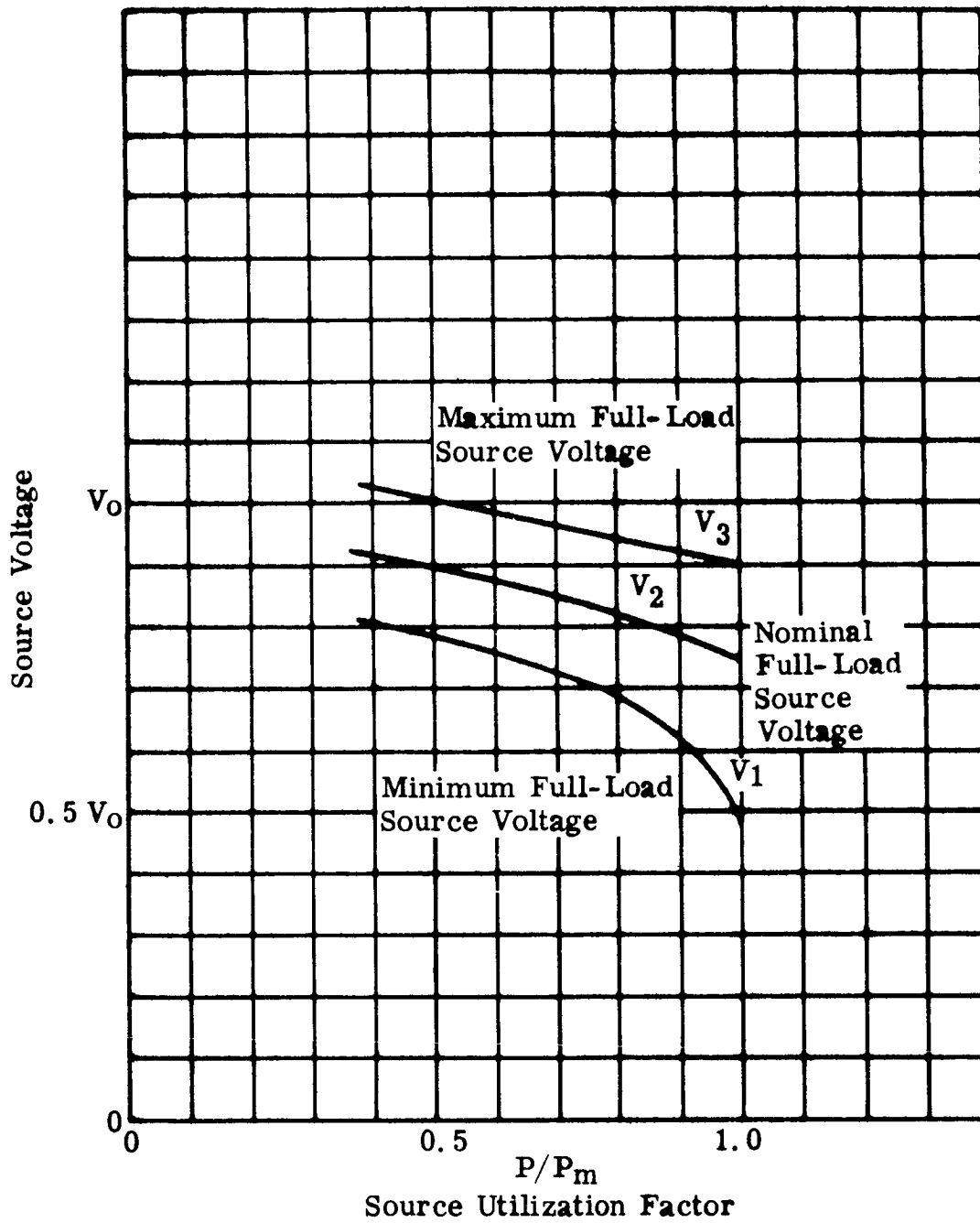


FIGURE 30

Nuclear-Thermionic Generator Voltage Vs. Utilization Factor, Task C and Task D

3. Converter Description

The converters selected for Tasks C and D are of the same basic design as that of Task B. The detail design is different, however, because of the difference in nominal source voltage. It will be recalled that in Task B the nominal source voltage is 150 volts while that for Task C is 50 volts and for Task D, 100 volts. A difference also exists in the mode of converter operation between the converters of Task B and the converters of Tasks C and D. The converters of Task B operate at a constant power output while the converters for Tasks C and D operate at constant current; however, both types of converters must be capable of operation over the full source voltage range.

If the nominal source voltage and voltage variation were the same for a converter which delivers constant-power as for a converter which delivers constant-current, the power output requirement would be the same for either converter at minimum source voltage. At maximum source voltage, the constant-current converter is required to deliver more power than the constant-power converter. However, a converter designed to operate at a constant power output over a specific source voltage variation, will be practically identical to one which operates at constant current over the same input voltage range despite the greater power output delivered by the constant-current converter at maximum source voltage. The converters for Task B, though rated at 30 kilowatts, with the exception of the power transformer, are capable of supplying approximately 40 kilowatts, the power requirement for the Task C and Task D converters.

The individual nominally rated 30-kw converters for Task C and Task D consist of several vapor tube thyatron inverter stages. The use of parallel inverter circuits for the individual 30-kw converters becomes necessary because the thyatron current rating would be exceeded with a single inverter at the reduced source voltages of Tasks C and D. Considering Figure 26, each inverter circuit is made up of three inverter stages for the Task C converters and two inverter stages for the converters of Task D. The input terminals of each stage are connected in parallel to the nuclear-thermionic source with each inverter stage output operating into a separate transformer primary. The transformer secondaries are connected in series to a common power rectifier providing a nominal 30-kw converter. Seventeen of these converters are connected in series through the rectifier assemblies to a single output filter network to provide a 510-kw power bus at 5 kilovolts. Six of these power channels comprise the 3.25-mw system.

All the converters used in Tasks C and D are identical. Each consists of an overcurrent protection circuit which works into the voltage

regulator. Therefore, should a fault occur, each of the converters in the 17 converter power channel can operate independently of the others. Although each of the converters in a power channel possesses a voltage regulator circuit, only four of the 17 converters in each group sense the output bus voltage and operate in a voltage regulating mode. The remaining 13 of the group operate in a nonregulating mode.

a. Voltage Regulation

With constant output voltage maintained to a fixed load resistance, each converter of Task C and Task D will carry a constant current. Voltage control is maintained by the voltage-regulating converters, which operate in exactly the same manner as described in Tasks A and B. Each of these converters senses a voltage proportional to the output bus voltage. If the output voltage is too high, one or more of the voltage-regulating converters will reduce its inverter controlled rectifier conduction angle and thus reduce the output voltage. No provision is made to divide output voltage between the voltage-regulating converters since they cannot assume more load than a nonregulating converter. Normally there will be slight differences in the voltage regulating level of each converter such that the inverter controlled rectifiers assume different conduction angles. The converter having the lowest regulator voltage setting will be the first to reduce its controlled conduction angle to decrease the output voltage; whereas the converter having the highest setting will be last. There is a natural tendency for the regulating converters to phase back one at a time as the source voltage increases.

The number of voltage-regulating converters in each group is a function of the nuclear-thermionic source voltage range over which the converters must operate. At the minimum source voltage, all converters, both regulating and nonregulating, are required to develop rated output. At the maximum source voltage, the voltage-regulating converters are cut back to essentially zero output, and only the nonregulating converters contribute to the load.

b. Overcurrent Protection

Overcurrent protection for the separate converters of Task C and Task D is accomplished in substantially the same manner as in Tasks A and B. One difference, as seen in Figure 31, is the method of current sensing that is performed on the a-c side of the rectifier assembly since current on the output side of the rectifiers is the same for all converters. Since the transformer secondary current is unique for the separate converters, an overcurrent condition can be sensed and a signal directed to the converter regulator to reduce the conduction angle of the inverter

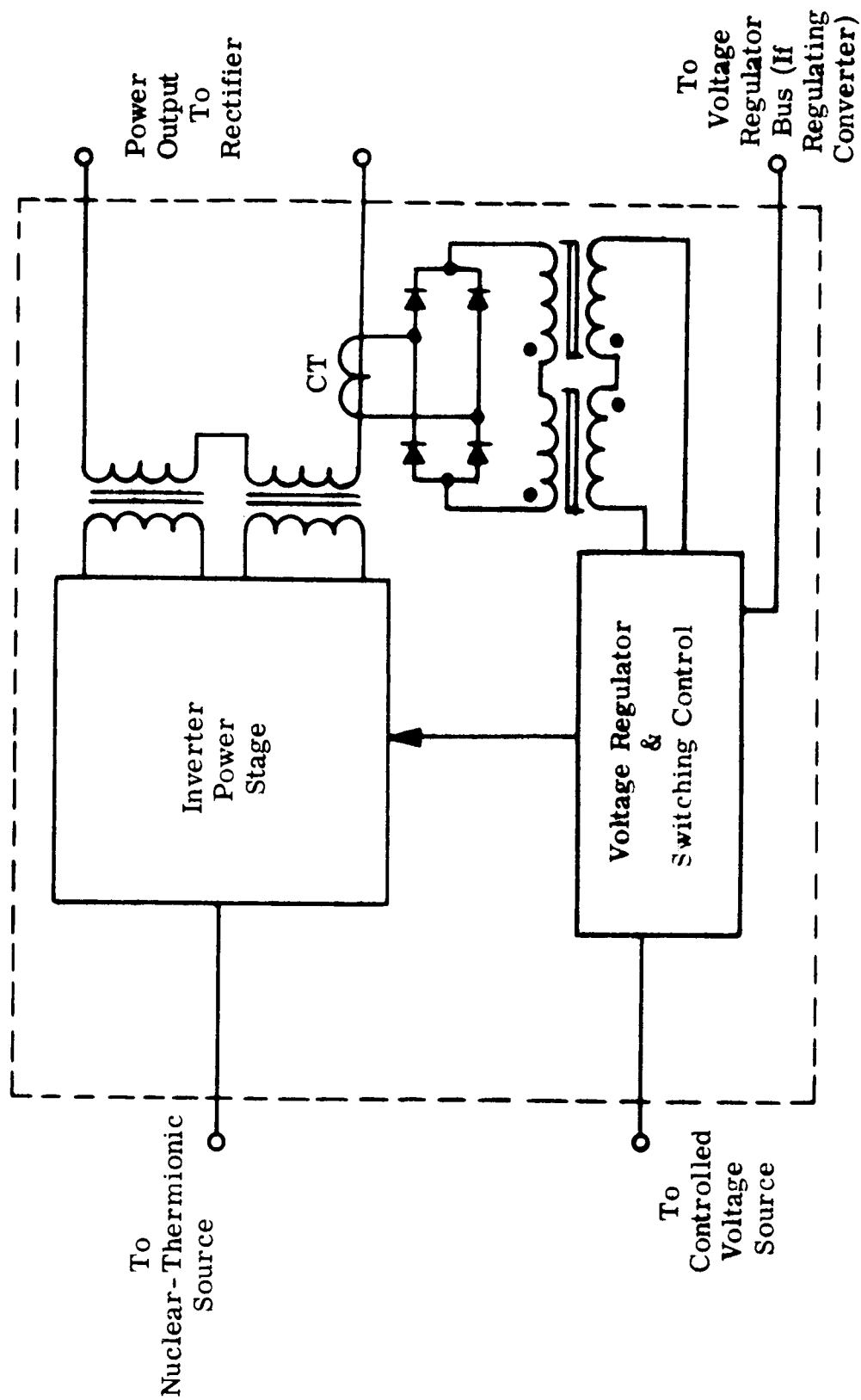


FIGURE 31

Converter Overcurrent Protection Technique With Current Transformer.
Task C and Task D

controlled rectifiers. An advantage in this sensing point is that a short circuit in the converter rectifier assembly can be detected and thus provide additional converter protection.

Design Criteria and Problem Areas

The design criteria and problem areas for the converters of Task C and Task D are the same as those discussed for the converters of Task B and, therefore, are not repeated here. Because the rectifier assembly current has increased to 102 amperes, vapor tube diodes rated at 72 amperes, rms, and 450 volts, PIV, were used for these converters.

Conceptual Data

Table 30 summarizes the major electrical parameters for the Task C and Task D converter system. Tabulated data of converter system weight, size, and power losses are presented in the mechanical design discussion which follows:

B. MECHANICAL SYSTEM

1. Design of Task C and Task D Converters

The inverter switching circuits, transformers, and rectifier assembly for a single 30-kw converter are contained in three separate packages as follows. The transformers and inverter-circuit inductors are contained in one common package and share a common coolant circuit. The vapor-tube rectifier assembly and the inverter circuit thyratrons and diodes share a second common package and coolant circuit. The inverter capacitors are contained in a third package and use a separate coolant circuit. As described in the discussion for the Task A and Task B converters, this type grouping allows lower structural weight than is possible by packaging the functional circuits separately. Choice in grouping is dictated by the maximum allowable component temperature of each functional block. Those having the same coolant temperature share the same coolant circuit. A block diagram depicting the three packages and showing coolant flow to them is given in Figure 32.

The frequency-reference oscillators, voltage regulators, drive amplifiers, overcurrent protection circuits, and output filter capacitors for one group of 17 converters comprising a 510-kw channel are contained in a single common package. The control circuits share a com-

TABLE 30

CONVERTER SYSTEM ELECTRICAL PARAMETERS, TASK C AND TASK D

	Task C Converter	Task D Converter
Nominal Source Voltage (volts)	50	100
Number of Isolated Power Channels	6	6
Power Output Per Channel (kw)	510	510
Number of Converters Per Channel	17	17
Number of Voltage Regulating Converters		
Per Channel	4	4
Maximum Continuous Power		
Output Per Converter (kw)	39.2	39.2
Maximum Output Voltage		
Rating of Converter (volts)	385	385
Minimum Output Voltage		
Rating of Converter (volts)	294	294
Output Current Rating of Converter (amps)	102	102
Maximum Input Voltage to Converter at Full Load (volts)	56.5	113
Minimum Input Voltage to Converter at Full Load (volts)	43.5	87
Inverter Switching Frequency (cps)	200	200
Nuclear-Thermionic Source		
Open-Circuit Voltage, V_O (volts)	57	114
Nuclear-Thermionic Source		
Short-Circuit Current, I_S (amps)	56,000	28,250
Weight Per Channel, Source Over Capacity Penalty (lbs)	3400	3400

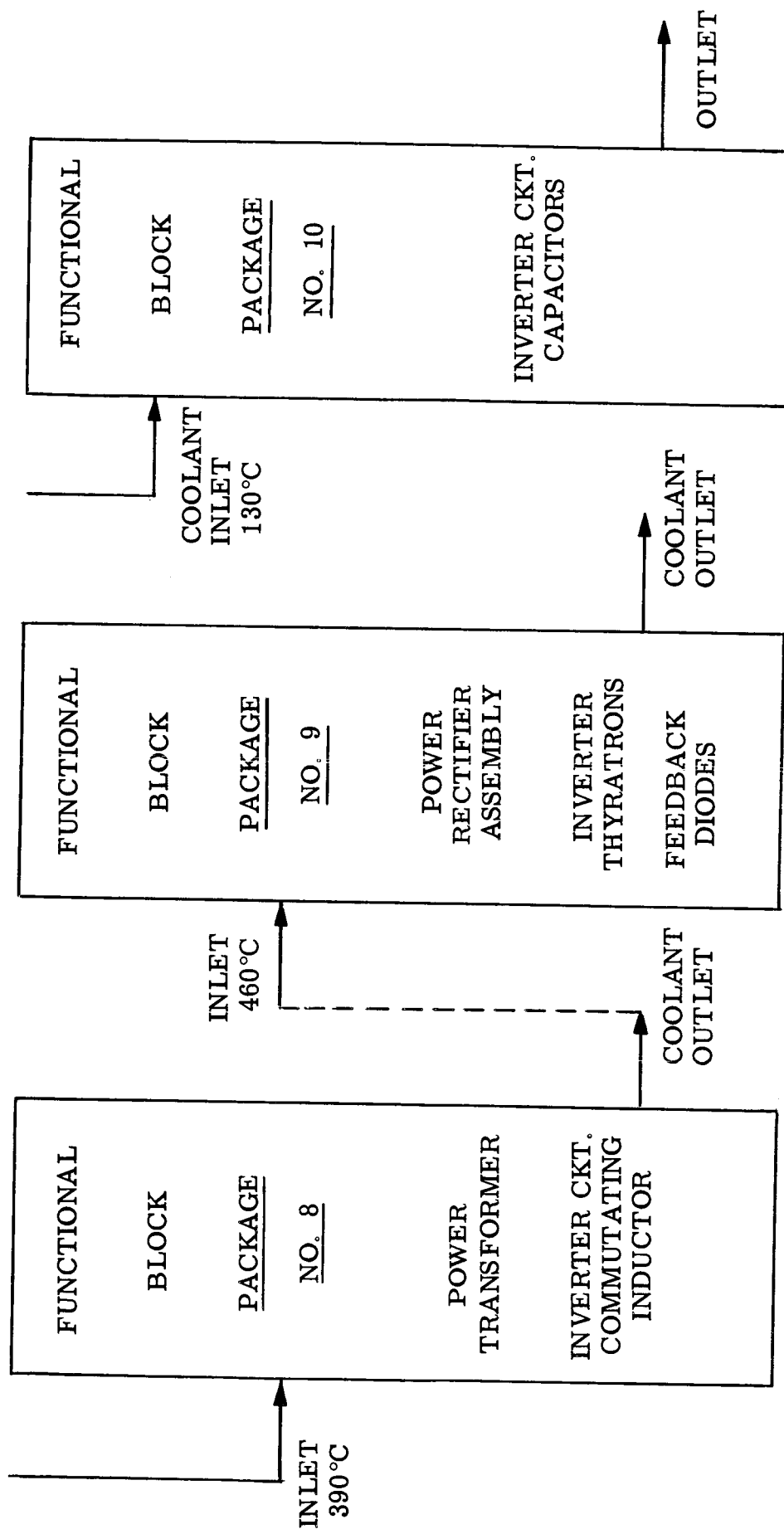


FIGURE 32

Block Diagram Of Mechanical Conceptual Design For 30-kw Converter,
Task C and Task D

mon cold plate, while the output filter capacitors are mounted on a separate cold plate because of a slightly different required coolant temperature.

A single output-filter inductor required for each 510-kw converter group is packaged separately. A block diagram, Figure 33, shows these two packages and the coolant flow to them.

Only two different coolant inlet temperatures are required for the converters of both Tasks C and D. A low temperature coolant system serves Package Numbers 10 and 11. A separate high temperature system is in series through Package Numbers 8 and 9 and serves Package Number 12.

The general design criteria and problem areas are the same for Tasks C and D as described previously for Tasks A and B.

2. Functional Block Package Numbers 8-12

Functional Block Package Number 8

The inverter commutating inductors and the power transformer for each 30-kw converter share a common package and coolant circuit. The mechanical construction, cooling means, and design criteria are the same as for Functional Block Package Number 6 of Task B.

Functional Block Package Number 9

The vapor-tube rectifier assembly, inverter circuit thyratrons, and energy feed back diodes for each 30-kw converter are included in a common package and share a common coolant circuit. The rectifier assembly vapor tube diodes and inverter circuit thyratrons have an allowable maximum envelope temperature of 600°C, while the inverter gas tube diodes are limited to 800°C. To simplify packaging, all three are mounted on a common coolant circuit with a 600°C device limit.

The tubes are flange-mounted directly to a cold plate, which has integral coolant ducts routed adjacent to them. The devices are cooled directly by conduction through columbium flanges to the cold plate. Flanges are adhesive bonded to the plate to reduce thermal resistance across the joint and are mechanically fastened to insure structural reliability. Cold plate and cooling tubes are of columbium.

In addition to the design criteria listed in the Task A and Task B mechanical design discussion, the following information was used to calculate data.

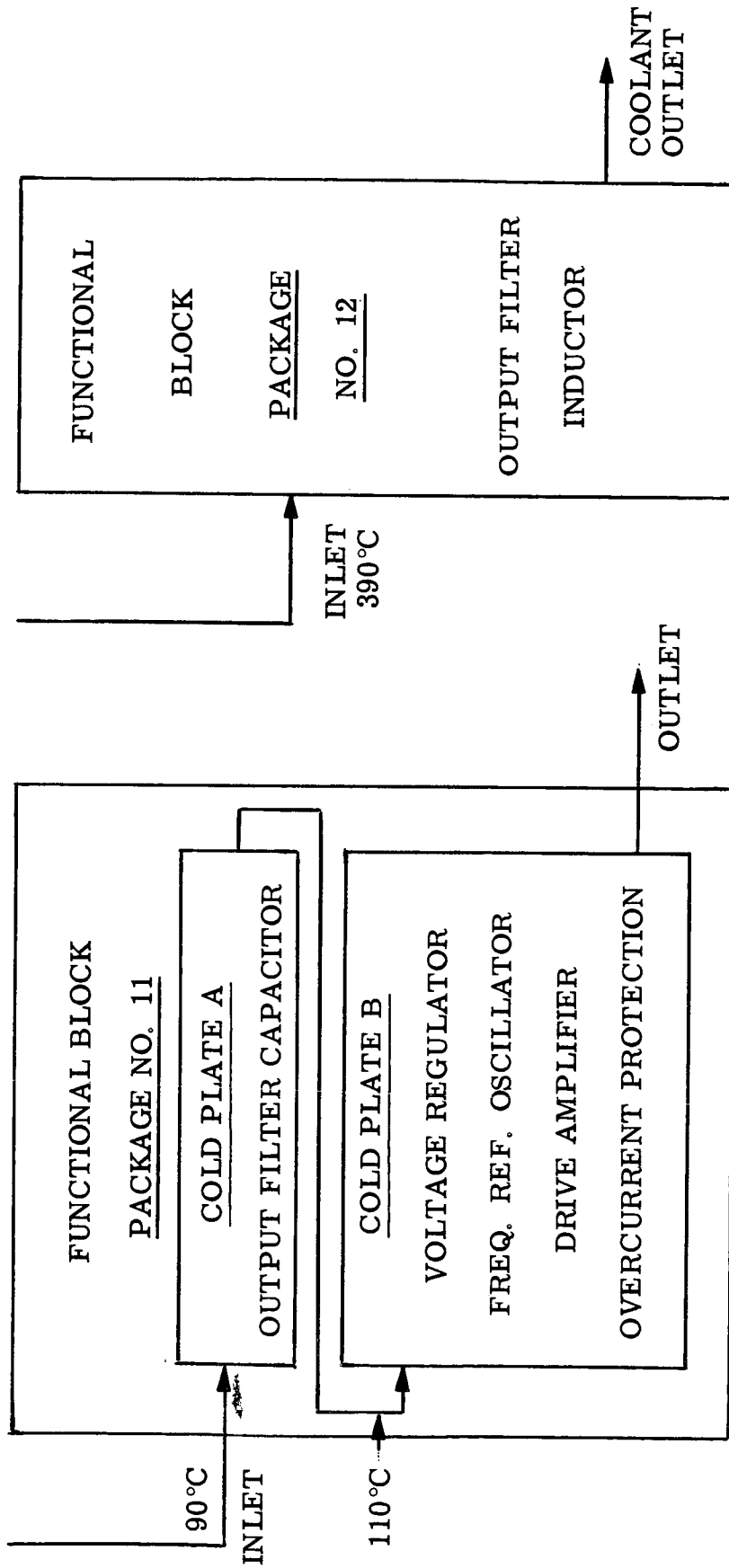


FIGURE 33

Block Diagram Of Mechanical Conceptual Design For 510-kw Converter Power Channel,
Task C and Task D

- a. Gas and vapor tube devices are assumed to have an allowable case temperature of 600°C , equivalent to the allowable grid and anode temperature. The coolant conduit wall temperature is 475°C .
- b. Total package weight, including insulation, coolant tubes, and structure, was assumed to be 3.8 times the total device weight.

Functional Block Package Number 10

The inverter capacitors for a 30-kw converter are contained in a third package with a separate low-temperature coolant circuit. The capacitors are mounted to a beryllium cold plate utilizing liquid metal coolant. Mechanical construction is similar to that used in Functional Block Package Number 2 of Task A. In addition to the design criteria listed in the Task A mechanical design discussion, the following information was used to determine the data.

- a. Inverter commutating capacitors have a maximum operating temperature of 180°C . This is approximately equivalent to a 25% derating of the rated allowable temperature. The coolant conduit wall temperature is 140°C .
- b. Supporting structure weight is 20 percent of the total weight. This is exclusive of the weight of the cold plate, insulation, and coolant tubing.

Functional Block Package Number 11

The voltage regulator, frequency reference oscillator, overcurrent protection circuit, and drive amplifier for the 510-kw converter channel have the same maximum allowable temperature and are grouped in a single package, sharing a common cold plate. The output filter capacitors are mounted on a separate cold plate included in the same package. A separate cold plate is used because the output filter capacitors require a coolant inlet temperature about 20°C below that for a common cold plate.

Mechanical construction and cooling means are the same as discussed for Functional Block Package Number 2 of Task A. In addition to the design criteria listed for the mechanical design of Task A, the following information was used to calculate data.

- a. Supporting structure weight is 20% of the total weight. This is exclusive of the weight of cold plate, insulation, and coolant tubing.

Functional Block Package Number 12

The output-filter inductor for the 510-kw converter channel is contained in an individual package with a separate high-temperature cold plate. The mechanical construction, cooling means, and design criteria are the same as for Functional Block Package Number 3 of Task A.

Conceptual Data

Weights, volumes, and power losses are given in Tables 31 and 32 for the individual functional circuits which make up the converters for Tasks C and D. Weights and volumes, with the exception of the output filter, are presented for a 30-kw converter. The values shown do not include source or thermal radiator penalties.

Weights, volumes, and losses are also presented for the 510-kw power channel which incorporates seventeen 30-kw converters. Data for the output filter, used with each group of 17 converters, are given in this tabulation. Six such groups make up the 3.25-mw converter system. Weights are shown for the converter system with and without source and thermal radiator penalties. The source-over-capacity penalty tabulated as a separate factor was determined from Figures 28 and 29 for Task C and Task D, respectively, at a P/P_m ratio of 0.6.

Results

The converter system for Task C provides a specific weight of 93.8 pounds per kilowatt when only components, structure, and cooling system are considered. This is increased to 104 pounds per kilowatt when all weight penalties are included. This corresponds to a specific weight of 37.5 and 46.6 pounds per kilowatt, respectively, for the Task D converter system.

The Task C converter system efficiency is 77.3% compared to 83.2% for the Task D converter system.

TABLE 31

WEIGHT, VOLUME, AND LOSS DATA FOR 510-KW CONVERTER POWER CHANNEL, TASK C

30-KW CONVERTER			510-KW GROUP			
	*Packaged Wt. (lb)	Volume (ft. ³)	*Packaged Wt. (lb)	- Packaged Wt. and Penalties (lb)	Volume (ft. ³)	Losses (kw)
Inverter Circuit Frequency: 200 Cycles Per Second						
Inverter Switching Circuit	2568.8	33.39	43600.0	44730.4	565.00	99.20
Transformer	171.0	0.97	2907.0	3208.1	16.42	26.64
Rectifier Assembly	11.4	0.31	194.0	353.3	5.27	14.50
Output Filter			899.0	929.7	6.80	2.70
Frequency Reference Oscillator	0.4	0.01	6.6	7.1	0.17	0.02
Voltage Regulator	2.0	0.03	34.0	39.1	0.51	0.22
Drive Amplifier	13.1	0.46	221.9	418.1	7.86	8.55
Overcurrent Protection	0.6	0.01	10.6	11.5	0.17	0.04
Subtotal	2767.3	35.09	47873.1	49697.3	602.20	151.87
Source-Over-Capacity Penalty				3400		
Total			47873.1	53097.3	602.20	151.87

WEIGHT, VOLUME, AND LOSS DATA FOR 3.25-MW CONVERTER SYSTEM

Total	287,239	318,584	3,613.2	911.2
Specific Wt. (lb kw)	93.8	104		
Converter System Eff. (%)				77.3

*Converter weight. Includes electrical components, structure and cooling system.
+Converter weight plus thermal radiator and source weight penalties.

NOTE: The totals for the 3.25-mw converter system are the results of 6 electrically isolated 510-kw converter groups.

TABLE 32

WEIGHT, VOLUME, AND LOSS DATA FOR 510-KW CONVERTER POWER CHANNEL, TASK D

	30-KW CONVERTER			510-KW GROUP		
	*Packaged Wt. (lb)	Volume (ft. 3)	*Packaged Wt. (lb)	+Packaged Wt. and Penalties (lb)	Volume (ft. 3)	Losses (kw)
Inverter Circuit Frequency:	200 Cycles Per Second					
Inverter Switching Circuit	890.4	12.31	15150.0	15824.7	209.70	58.04
Transformer	157.2	0.86	2675.0	2919.1	14.60	21.60
Rectifier Assembly	11.4	0.31	194.0	353.3	5.27	14.50
Output Filter			899.0	929.7	6.80	2.70
Frequency Reference Oscillator	0.4	0.01	6.6	7.1	0.17	0.02
Voltage Regulator	2.0	0.03	34.0	39.1	0.51	0.22
Drive Amplifier	3.7	0.31	148.2	283.1	5.27	5.88
Overcurrent Protection	0.5	0.01	10.6	11.5	0.17	0.04
Subtotal	1070.7	13.34	19117.4	20367.6	242.49	103.00
Source-Over-Capacity Penalty				3400		
Total			19117.4	23767.6	242.49	103.0

WEIGHT, VOLUME, AND LOSS DATA FOR 3.25-MW CONVERTER SYSTEM

Total						
Specific Wt. (lb./kw)	114,704	142,606	1,454.9	618.0		
Converter System Eff. (%)	37.5	46.6		83.2		

*Converter weight. Includes electrical components, structure and cooling system.
+Converter weight plus thermal radiator and source weight penalties.

NOTE: The totals for the 3.25-mw converter system are the results of 6 electrically isolated 510-kw converter groups.

SECTION V
CONCLUSIONS AND RECOMMENDATIONS

CONCLUSIONS AND RECOMMENDATIONS

This report presents the conceptual data for several d-c to d-c converters. Analyses and recommendations have been made in the preceding sections for the functional blocks which make up the converters. This section discusses conclusions and recommendations concerning the overall d-c to d-c converters.

A. CONCLUSIONS

1. The results of the study show that converters become more attractive at the higher input voltages. Converters with higher input voltages are more efficient, less complex, and lighter than those with lower input voltages. The voltage limit is determined by the voltage rating of the individual circuit components, particularly the switching devices, and the source.
2. The weight, efficiency, and volume of the converters are dependent on the inverter switching frequency. It is not obvious how the converter parameters vary because the parameters of each functional block do not change in the same direction or magnitude with a change in frequency. The switching frequency that results in an optimum converter design can be determined by investigating the converter weight as a function of frequency when source and thermal radiator penalties are considered because of power losses. This was performed for the Task A converters. A frequency of 2300 cycles per second resulted.
3. The Task B converter, using high temperature vapor and gas tube devices, weighs more, has a larger volume, and is less efficient than the Task A converter using silicon semiconductors. When the effects of radiation shielding, transmission line weight, and transmission line cooling requirements are considered, the Task B converter system weighs less than the Task A system. The higher operating temperature and resistance to nuclear radiation inherent in the tube devices offset the basic converter weight disadvantage. It should be recalled, however, that the high temperature vapor tube thyratrons and gas tube diodes are not available at this time, but are presently under study and development. The characteristics for these devices presented in this report are design objectives.
4. Multiple channel systems offer a means to improve reliability through redundancy. This was the case for Task A and Task B of this study where 102 converters, rated at 30 kilowatts each, were operated from separate sources into separate engine loads. With

identical requirements and equal voltage inputs and outputs, a group of such converters working together from a properly rated power source will weigh less than a single converter operating from a single source. This occurs because, with proper grouping, it is possible to eliminate the input filter and reduce the output filtering requirements. Therefore, a compromise must be reached between maximum reliability and flexibility and system weight.

5. The source voltage variation characteristic becomes a significant factor in converter weight. A large source voltage variation about a specific nominal value requires a heavier converter than with a smaller voltage variation about the same nominal value. This occurs because the converter with the greater input voltage range must contain components which will permit operation at maximum input current when the source voltage is minimum, and the components must be capable of withstanding the higher stresses at maximum input voltage. These factors result in increased component rating, size, and weight.

To reduce the source voltage variation requires a source with a lower internal impedance so that the internal voltage drop will be less. This requires a source with a power capacity greater than required.

The lowest-weight converter-source system will result, therefore, in a compromise between source capacity and converter capacity.

B. RECOMMENDATIONS

It is recommended that future efforts be directed to building several breadboard units with a preferable rating of 30 kilowatts. These breadboards should be built with power silicon semiconductors and vapor tube and gas tube devices. Although the vapor tube and gas tube device converter system showed a weight advantage when compared with the silicon semiconductor converter system, the weight difference was less than 4%. At this point, in a development program, these systems can be considered practically equal and should be encouraged equally until a very decisive factor eliminates one or the other. It will be the purpose of the breadboard program to confirm converter operation, weight, size, and efficiency when operating into an ion engine simulated load from a source simulating a nuclear-thermionic characteristic.

At this time, lower temperature counterparts with similar operating characteristics and equivalent rating could possibly be substituted for the high temperature tube devices.

SECTION VI
BIBLIOGRAPHY

BIBLIOGRAPHY

Bedford, B. D. and Hoft, R. G., Principles of Inverter Circuits, John Wiley and Sons, Inc., 1964.

The Effect of Nuclear Radiation on Electronic Components, Including Semiconductors, REIC Report No. 36, prepared by Battelle Memorial Institute Information Center, October 1, 1964.

Investigation of Silicon Controlled Rectifiers for Static Power Conversion, Final Report, ASTIA-AD272626, Signal Corps. Contract DA36-0395C-85381, April to July 1961.

Jones, Dwight V., Turn-Off Circuits for Controlled Rectifiers, August 1960.

Kotnik, J. T. and Sater, B. L., "Power-Conditioning Requirements for Ion Rockets," IEEE Transaction on Aerospace, Vol. 2, No. 2, April, 1964.

McMurray, W. and Shattuck, D. P., "A Silicon Controlled Rectifier Inverter with Improved Commutation," AIEE Transactions, Part I, Communications and Electronics, Vol. 80, 1961.

Milnes, A. G., Transducers and Magnetic Amplifiers, MacMillan & Co. Ltd., London, 1957.

Radiation-Effects State of the Art, REIC Report No. 34, prepared by Battelle Memorial Institute Information Center, June 30, 1964.

Reactor Shielding Design Manual, TID-7004, prepared by Naval Reactor Branch, Division of Reactor Development, March, 1956.

Reference Data for Radio Engineers, 4th Edition, American Book, Stratford Press Inc., 1956.

SCR Power Inverter Study, Quarterly Progress Report, ASTIA-AD282985, Contract No. DA36-039SC-88965, Oct. 1961 to Jan. 1962.

Space Electric Power System Study, Vol. 1, Final Report, prepared by Westinghouse Electric Corp., prepared for National Aeronautics and Space Administration, Contract NAS5-1234, Dec., 1962.

Space Electric Power Systems Study, Vol. 5, Final Report, prepared by Westinghouse Electric Corp., prepared for National Aeronautics and Space Administration, Contract NAS5-1234, Amendment 6, Dec. 3, 1963.

Stover, John B., "Electric Breakdown and Arcing in Experimental Ion Thrustor Systems," AIAA Paper No. 63057, presented at Electric Propulsion Conference, March 1963.

Thermionic Nuclear Space Powerplant, Vol. II, Quarterly Progress Report, prepared by Pratt and Whitney Aircraft, prepared for National Aeronautics and Space Administration, Contract NASw-360, July to Sept. 1962.

SECTION VII

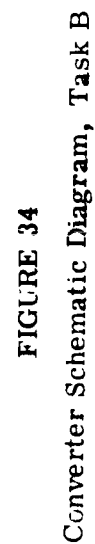
APPENDIX

COMPUTER PROGRAMING INFORMATION

APPENDIX

The analog computer programing information used on the Task B converter is as follows.

1. Converter schematic diagram.
2. Circuit describing equations for different modes of converter operation.
3. Analog diagrams of converter.
4. Truth statements for mode control.
5. Logic for thyratrons.
6. Computer potentiometer settings.
7. Circuit parameters.



DESCRIBING EQUATIONS:

Refer to Figure 34 for the symbol identification used in the describing equations presented for the nine different modes of circuit operation.

Mode 1

Conditions for Mode 1. $0 < V_2 < E_i$; $0 < V_3 < E_i$

1. $(E_S - E_i) (R_S) = I_S$
2. $I_1 = I_S - I_2$
3. $E_i = I_1 / \eta C_1 S$
4. $I_3 = \frac{E_i - V_1 - V_T}{\eta S L_1 / 2} \Bigg]_0^+$

η = analog time scale
(Assuming that A and B
cannot conduct simultane-
ously.)
5. $I_4 = \frac{V_1 - V_T}{\eta S L_1 / 2} \Bigg]_0^+$

(Same assumption as made
for I_3 .)
6. $I_7 = I_3$ when "A" is on.
7. $I_7 = -I_4$ when "B" is on.
8. $I_5 = S C_2 \eta (E_i - V_1)$
9. $I_6 = I_5 + I_7 - I_8$
10. $V_1 = \frac{I_6}{\eta C_3 S}$
11. $I_8 = I_{10} \frac{N_S}{N_P}$
12. $I_2 = I_3 + I_9 = I_7 + I_9$, when "A" is on (I_7 is +)
13. $I_9 = I_5 + I_{11}$
14. $I_2 = I_9$ when "B" is on.

$$15. \quad V_2 = (V_1 - V_4) (1-k) + V_4$$

$$V_2 = V_1 (1-k) + kV_4$$

$$16. \quad I_{11} = I_{16} - I_{12}$$

$$17. \quad I_{16} = I_{26} - I_{14}$$

$$18. \quad I_{26} = I_{21} + I_{24}$$

$$19. \quad I_{11} = -I_{12} - I_{14} + I_{21} + I_{24}$$

$$20. \quad V_3 = (V_1 - V_4) k + V_4$$

$$V_3 = kV_1 + V_4 (1-k)$$

$$21. \quad I_{20} = I_8$$

$$22. \quad I_{27} = \left. \frac{V_6 - E_O}{\eta L_3 S} \right]_0^+$$

$$23. \quad I_O = \frac{E_O}{R_L}$$

$$24. \quad I_{28} = I_{27} - I_O$$

$$25. \quad E_O = \frac{I_{28}}{\eta C_6 S} = \frac{(I_{27} - I_O)}{\eta C_6 S}$$

$$26. \quad V_6 = V_5 \Big]_0^+$$

$$27. \quad I_{10} = I_{27} \text{ synchronized with } V_5 \text{ when } V_6 = V_5$$

$$28. \quad V_5 = (V_1 - V_4) \frac{N_s}{N_p}$$

Mode 2

Conditions for Mode 2. $V_2 < -V_D$; $0 < V_3 < E_i$

$$29. \quad V_1 = \frac{-(V_4 + V_D)k}{1-k}$$

$$30. \quad I_6 = nC_3SV_1$$

$$31. \quad I_8 = I_7 + I_5 - I_6$$

$$32. \quad I_{20} = I_{19}$$

$$33. \quad I_{20}(1-k) + I_8k = I_{10} N_S/N_P$$

$$I_{20} = \frac{I_{10}N_S}{(1-k)N_P} - \frac{I_8k}{1-k}$$

$$34. \quad I_{17} = I_8 - I_{19} = I_8 - I_{20}$$

$$35. \quad I_{13} = -I_{17}$$

$$36. \quad I_{12} = I_{14} = I_{15} = 0$$

Switch to a mode where $0 < V_2 < E_i$ when I_{17} becomes positive or zero.

Mode 3

Conditions for Mode 3. $V_2 > E_i + V_D$; $0 < V_3 < E_i$

$$37. \quad V_1 = \frac{(E_i - V_4 - V_D)k + E_i}{1-k}$$

$$38. \quad I_6 = nC_3SV_1$$

$$39. \quad I_8 = I_7 + I_5 - I_6$$

$$40. \quad I_{20} = I_{19}$$

$$41. \quad I_{20} = \frac{I_{10}N_S}{(1-k)N_P} - \frac{I_8k}{1-k}$$

$$42. \quad I_{17} = I_8 - I_{19} = I_8 - I_{20}$$

$$43. \quad I_{12} = I_{17}$$

$$44. \quad I_{13} = I_{14} = I_{15} = 0$$

Switch to a mode where $0 < V_2 < E_i$ when I_{12} becomes zero or negative.

Mode 4

Conditions for Mode 4. $V_2 < -V_D$; $V_3 < -V_D$; $I_{10} = 0$

$$45. \quad V_1 = V_4 = -V_D$$

$$46. \quad I_5 = I_6 = I_{12} = I_{14} = I_{21} = I_{22} = 0$$

$$47. \quad I_8 = I_7$$

$$48. \quad I_{20} = -I_{23}$$

$$49. \quad I_{19} = \frac{-kI_8}{1-2k} - \frac{kI_{20}}{1-2k}$$

$$50. \quad I_{17} = I_8 - I_{19}$$

$$51. \quad I_{18} = I_{19} - I_{20}$$

Switch to the appropriate mode when I_{17} or I_{18} goes to zero or positive.

Mode 5

Conditions for Mode 5. $V_3 < 0$; $0 < V_2 < E_i$

$$52. \quad V_4 = \frac{-V_1 k}{1-k}$$

$$53. \quad I_{22} = nC_5 S V_4$$

$$54. \quad I_{20} = I_{22} - I_{21} - I_{23}$$

$$55. \quad I_8 = I_{19}$$

$$56. \quad I_8 = \frac{I_{10}N_s}{(1-k)N_p} - \frac{I_{20}k}{1-k}$$

$$57. \quad I_{18} = I_{19} - I_{20}$$

$$58. \quad I_{15} = -I_{18}$$

$$59. \quad I_{14} = I_{12} = I_{13} = 0$$

Switch to a mode where $0 < V_3 < E_i$ when I_{18} becomes positive or zero.

Mode 6

Conditions for Mode 6. $V_3 > E_i$; $0 < V_2 < E_i$

$$60. \quad V_4 = \frac{(E_i - V_1)k + E_i}{1-k} = \frac{E_i - V_1k}{1-k}$$

$$61. \quad I_{22} = nC_5SV_4$$

$$62. \quad I_{20} = I_{22} - I_{21} - I_{23}$$

$$63. \quad I_8 = I_{19}$$

$$64. \quad I_8 = \frac{I_{10}N_s}{(1-k)N_p} - \frac{I_{20}k}{1-k}$$

$$65. \quad I_{18} = I_{19} - I_{20}$$

$$66. \quad I_{14} = I_{18}$$

$$67. \quad I_{15} = I_{12} = I_{13} = 0$$

Switch to a mode where $0 < V_3 < E_i$ when I_{18} becomes negative or zero.

Mode 7

Conditions for Mode 7. $V_3 > E_i + V_D$; $V_2 > E_i + V_D$; $I_{10} = 0$

$$68. \quad V_1 = V_4 = E_i + V_D$$

$$69. \quad I_5 = I_6 = I_{21} = I_{22} = I_{13} = I_{15} = 0$$

$$70. \quad I_8 = I_7$$

$$71. \quad I_{20} = -I_{23}$$

$$72. \quad I_{19} = \frac{k(-I_8 - I_{20})}{1 - 2k}$$

$$73. \quad I_{17} = I_8 - I_{19}$$

$$74. \quad I_{18} = I_{19} - I_{20}$$

$$75. \quad I_{12} = I_{17}$$

$$76. \quad I_{14} = I_{18}$$

Switch to the appropriate mode whenever I_{17} or I_{18} goes to zero or negative.

Mode 8

Conditions for Mode 8. $V_2 < -V_D$; $V_3 > E_i + V_D$

$$77. \quad V_1 = \frac{-(E_i + 2V_D)k}{1 - 2k}$$

$$78. \quad V_4 = -V_1 + E_i$$

$$79. \quad I_5 = I_6 = I_{21} = I_{22} = I_{12} = I_{15} = 0$$

$$80. \quad I_8 = I_7$$

$$81. \quad I_{20} = -I_{23}$$

$$82. \quad I_{19} = \frac{-kI_8}{1 - 2k} - \frac{kI_{20}}{1 - 2k} + \frac{I_{10}N_S}{(1 - 2k)N_p}$$

$$83. \quad I_{17} = I_8 - I_{19}$$

$$84. \quad I_{13} = -I_{17}$$

$$85. \quad I_{18} = I_{19} - I_{20}$$

$$86. \quad I_{14} = I_{18}$$

Switch to the appropriate mode whenever I_{17} goes to zero or positive or I_{18} goes to zero or negative.

Mode 9

Conditions for Mode 9. $V_2 > E_i$; $V_3 < 0$

$$87. \quad V_1 = \frac{E_i (1-k)}{1-2k}$$

$$88. \quad V_4 = \frac{-E_i k}{1-2k}$$

$$89. \quad I_5 = I_6 = I_{21} = I_{22} = I_{13} = I_{14} = 0$$

$$90. \quad I_8 = I_7$$

$$91. \quad I_{20} = I_{23}$$

$$92. \quad I_{19} = \frac{-kI_8}{1-2k} - \frac{kI_{20}}{1-2k} + \frac{I_{10}N_S}{(1-2k)N_p}$$

$$93. \quad I_{17} = I_8 - I_{19}$$

$$94. \quad I_{12} = I_{17} \Big]_0^+$$

$$95. \quad I_{18} = I_{19} - I_{20}$$

$$96. \quad I_{15} = -I_{18} \Big]_0^+$$

Switch to the appropriate mode whenever I_{12} or I_{15} goes to zero.

TRUTH STATEMENTS FOR MODE CONTROL:

T1 = K00 "on", see Figure 35

T2 = K01 "on", see Figure 35

T3 = K02 "on", see Figure 36

Mode	T1	T2	T3	$A=V_3 > E_i$	$B=V_3 < 0$	$C=V_2 > E_i$	$D=V_2 < 0$	I_{17}	I_{18}	I_{12}	I_{14}	Relays On
1	0	0	0	0	0	0	0	0	0	0	0	0, 1, 2, 4, 6
2	1	0	0	0	0	0	1	-	0	0	0	1, 2, 4
3	1	0	0	0	0	1	0	+	0	+	0	1, 2, 4, 5, 6
4	1	1	1	0	1	0	1	-	-	0	0	-----
5	0	1	0	0	1	0	0	0	-	0	0	0, 2, 6
6	0	1	0	1	0	0	0	0	+	0	+	0, 2, 3, 4, 6
7	1	1	1	1	0	1	0	+	+	+	+	3, 4, 5, 6
8	1	1	1	1	0	0	1	-	+	0	+	3, 4
9	1	1	1	0	1	1	0	+	-	+	0	5, 6

Refer to Figure 36 for the following equations.

$$T1 = C + D + BD + AC + AD + BC = C + D$$

$$T2 = BD + B + A + AC + AD + BC = A + B$$

$$T3 = BD + AC + AD + BC = (A+B) (C+D) = (T1) (T2)$$

LOGIC FOR THYRATRONS:

TA = Thyatron A on.

TB = Thyatron B on.

TC = Thyatron C on.

TD = Thyatron D on.

GA = Clock Pulse for A

GB = Clock Pulse for B

GC = Clock Pulse for C

GD = Clock Pulse for D

$$E = 2 V_1 > E_i$$

$$M = V_1 > 0$$

$$H = 2 V_4 > E_i$$

$$P = V_4 > 0$$

Assuming zero reverse current:

$$TA = GA \cdot E + T_B'$$

$$TA' = T_B$$

$$T_B = GB \cdot E' + M \cdot TA' \cdot GB$$

$$TC = GC \cdot H + TD'$$

$$TC' = TD$$

$$TD = GD \cdot H' + P \cdot TC' \cdot GD$$

COEFFICIENT POTENTIOMETER SETTINGS:

A.	$E_s/200$	B1.	$N_s/100N_p$
B.	$5/nC_1$	C1.	0.5000
C.	$1/5nL_1$	D1.	$1/(1-k)10$
D.	$1/5nL_1$	E1.	$k/(1-k)$
G.	$1/4nC_3$	F1.	0.1000
H.	$1/5nL_2$	G1.	$nC_3/5$
I.	0.1000	H1.	$k/(1-k)$
J.	$nC_2/5$	I1.	$N_s/100N_p(1-k)$
K.	$1/5nL_2$	K1.	0.5000
N.	$nC_4/5$	L1.	0.5000
P.	0.1000	M1.	$k/(1-2k)$
Q.	$1/4nC_5$	N1.	0.0300
R.	$1-k$	P1.	$k/(1-2k)$
S.	k	Q1.	$(1-k)/(1-2k)5$
T.	k	R1.	$2k^2/(1-2k)(1-k)$
U.	$1-k$	S1.	0.5000
V.	$N_s/50N_p$	T1.	0.5000
W.	$N_s/50N_p$	U1.	0.5000
X.	$100/nL_3$	V1.	0.5000
Y.	$100/nL_3$	W1.	0.5000
Z.	$1/100nC_6$	X1.	$1/(1-k)10$
A1.	$1/nR_L C_6$	Y1.	$k/(1-k)$

Z1.	0. 1000	X2.	w/100n
A2.	0. 5000	Y2.	0. 3180
B2.	0. 5000	Z2.	0. 3180
C2.	$nC_5/5$	A3.	0. 2000
D2.	$k/(1-k)$	B3.	0. 2000
E2.	$N_S/100N_p(1-k)$	C3.	0. 2000
F2.	$k/(1-2k)$	D3.	0. 2000
G2.	$k/(1-2k)$	E3.	0. 2000
H2.	$(1-k)/(1-2k)10$	F3.	0. 2000
I2.	$k/(1-2k)$	G3.	0. 2000
J2.	0. 4000	H3.	0. 2000
K2.	0. 0050	I3.	0. 0500
L2.	0. 4000	J3.	0. 0500
M2.	0. 0050	K3.	0. 0500
N2.	0. 0001	L3.	0. 0500
P2.	0. 0001	M3.	$\theta/360$
Q2.	0. 1000	N3.	0. 2000
R2.	0. 1000	P3.	0. 2000
S2.	0. 1000	Q3.	0. 2000
T2.	W/n	R3.	0. 2000
U2.	W/n	S3.	0. 0500
V2.	0. 5000	T3.	0. 0500
W2.	w/100n	U3.	0. 0500

V3. 0.0020

W3. 0.0500

X3. 0.2400

Y3. $V_T/500nL_2$

Z3. $V_T/500nL_1$

A4. $V_D/200$

B4. $V_D/200$

C4. $N_S/100N_p(1-2k)$

D4. 0.0050

E4. $N_S/100N_p(1-2k)$

F4. $100/R_L$

CIRCUIT PARAMETERS:

Thermionic Generator Characteristics

X	V_O (P. U.)	I_S (P. U.)	Y
100	0.0	1.0	84.6
90	0.1	0.96	81.22
80	0.2	0.91	76.99
70	0.3	0.84	71.06
60	0.4	0.76	64.30
50	0.5	0.66	55.84
40	0.6	0.55	46.53
30	0.7	0.43	36.38
20	0.8	0.29	24.53
10	0.9	0.15	12.69
0	1.0	0	0

$V_O = 1$ P. U. = 200 volts

$I_S = 1$ P. U. 846 amperes

1. $R_L = 833.3$ ohms
2. $L_3 = 0.338$ hy.
3. $C_6 = 3.04$ μ fd.
4. $N = \frac{N_S}{N_P} = 30$
5. $C_2, C_3, C_4, C_5 = 410$ μ fd.
6. $L_1, L_2 = 112$ μ hy.

7. $C_1 = 0.1, 0.05, 0.025, 0.0125$ fd.
8. $f = 1000$ cps
9. $k = 0.25$
10. $\theta = 0^\circ, 45^\circ, 90^\circ$

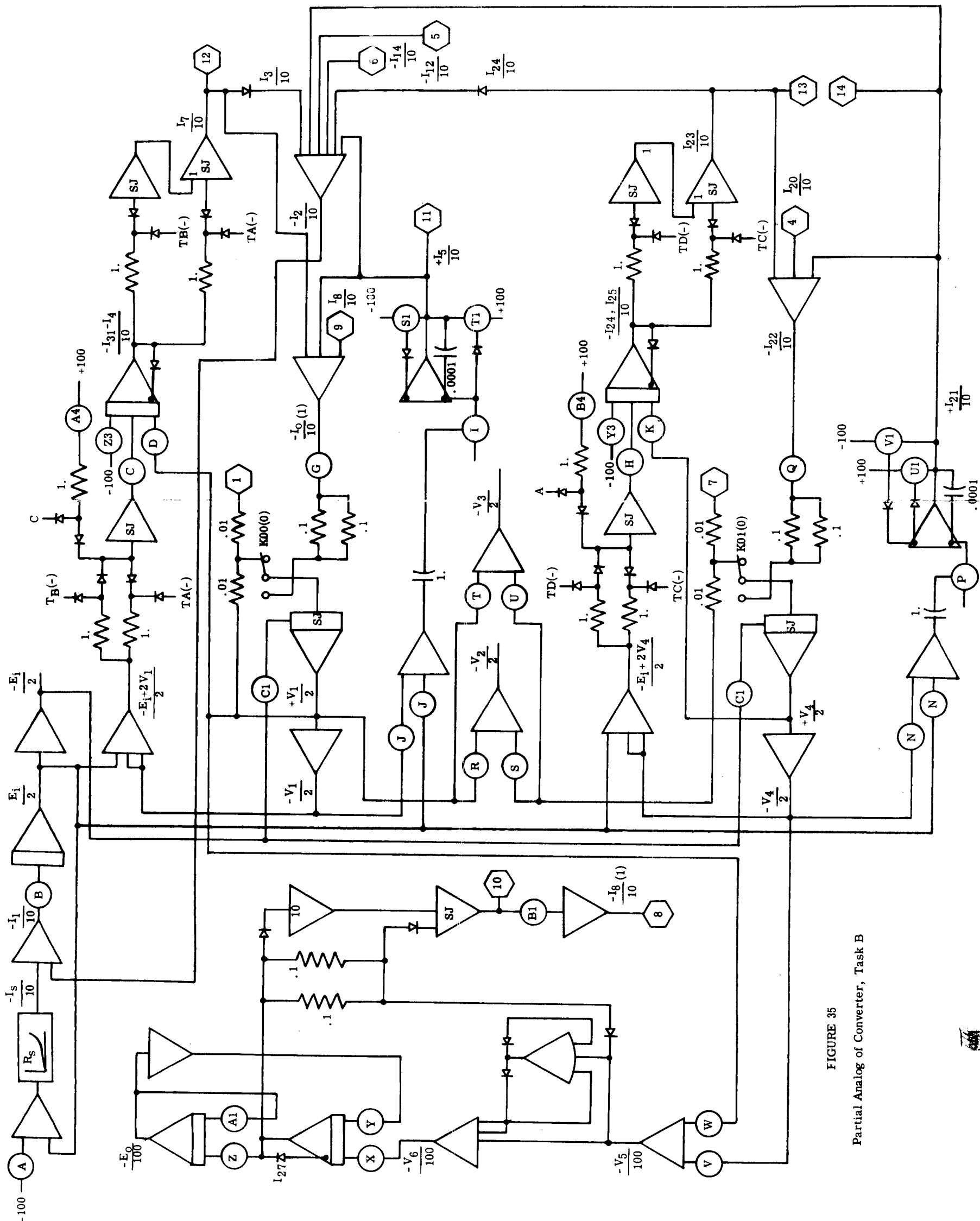


FIGURE 35
Partial Analog of Converter, Task B

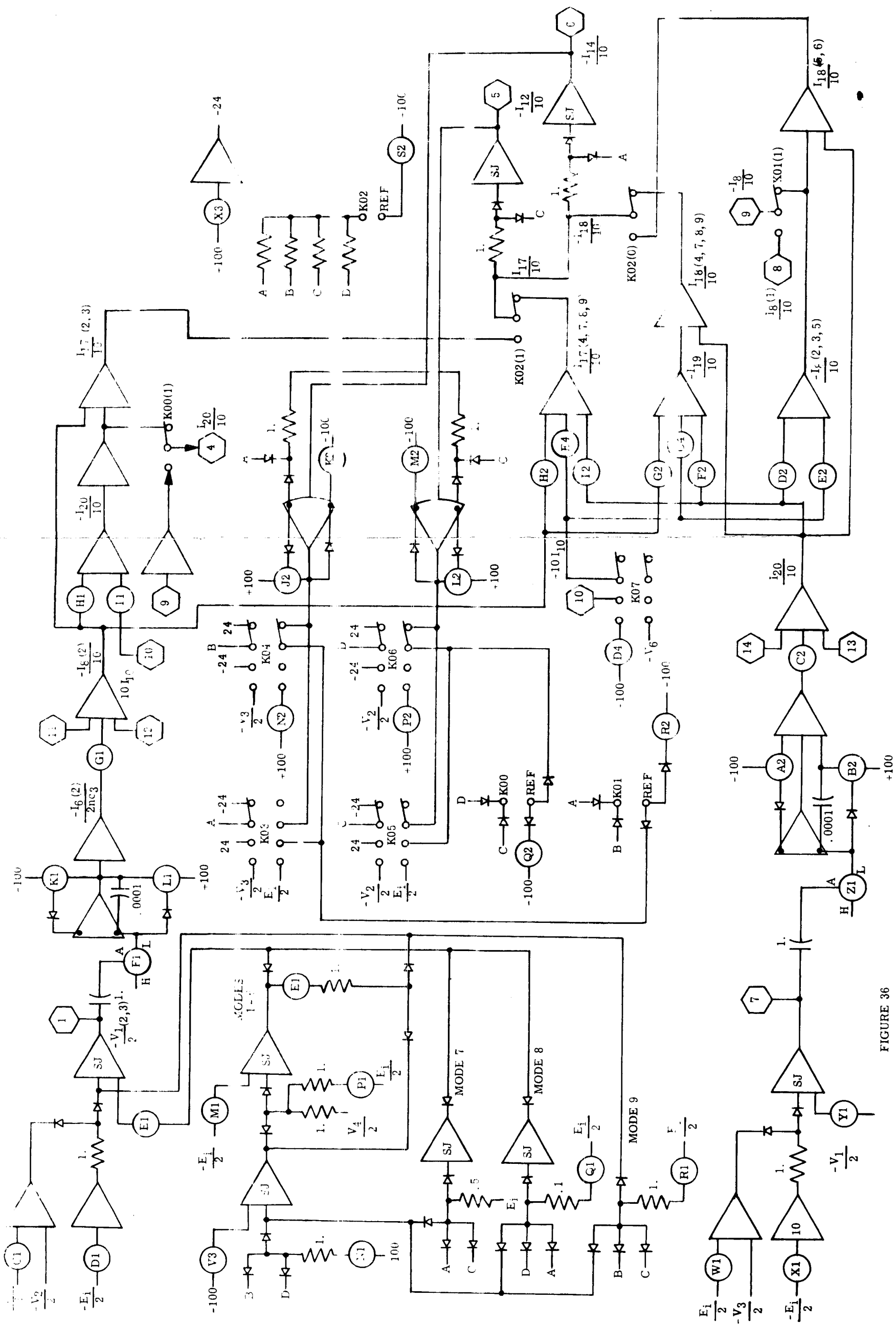


FIGURE 36
Partial Analog of Converter, Task B

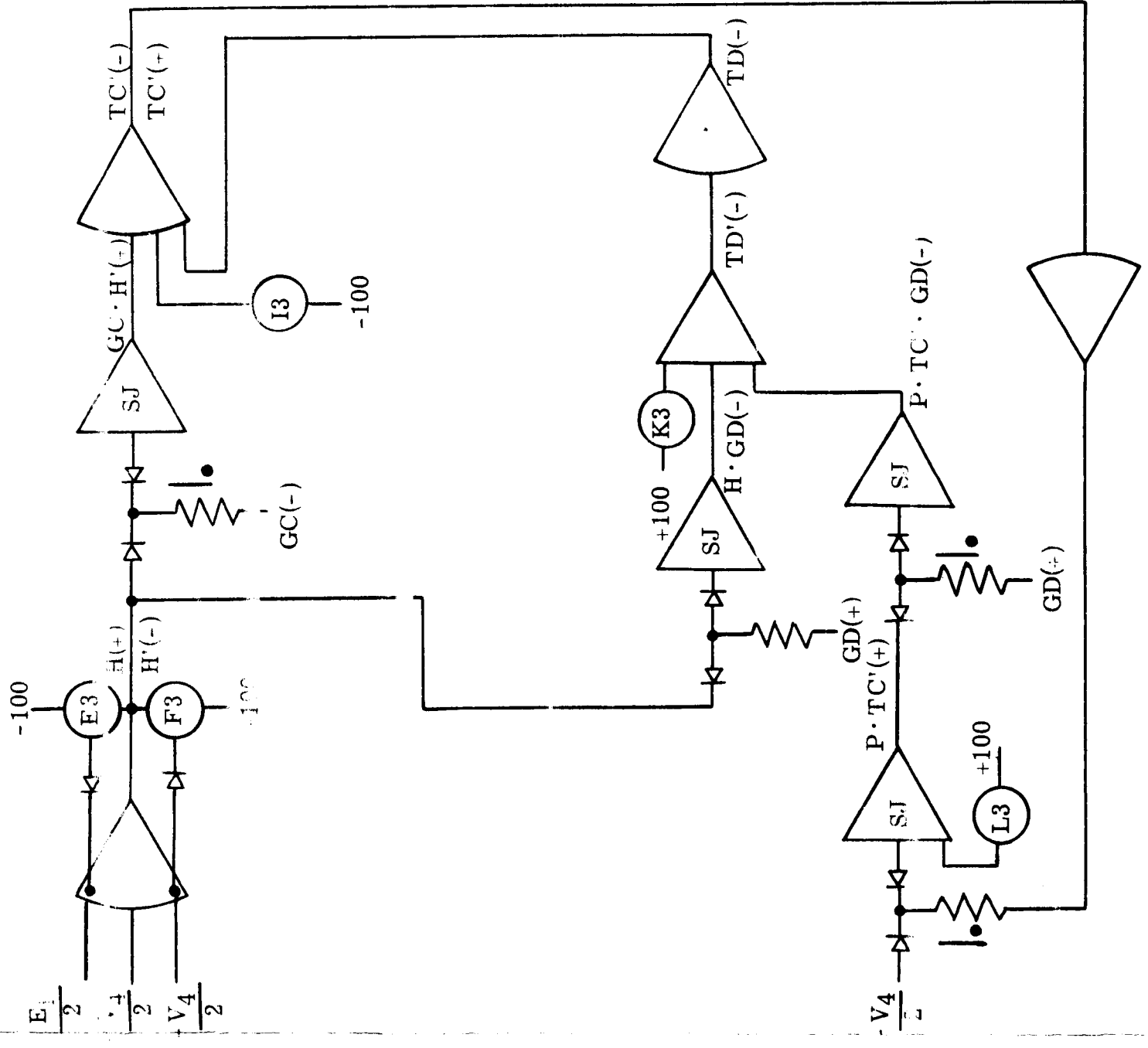
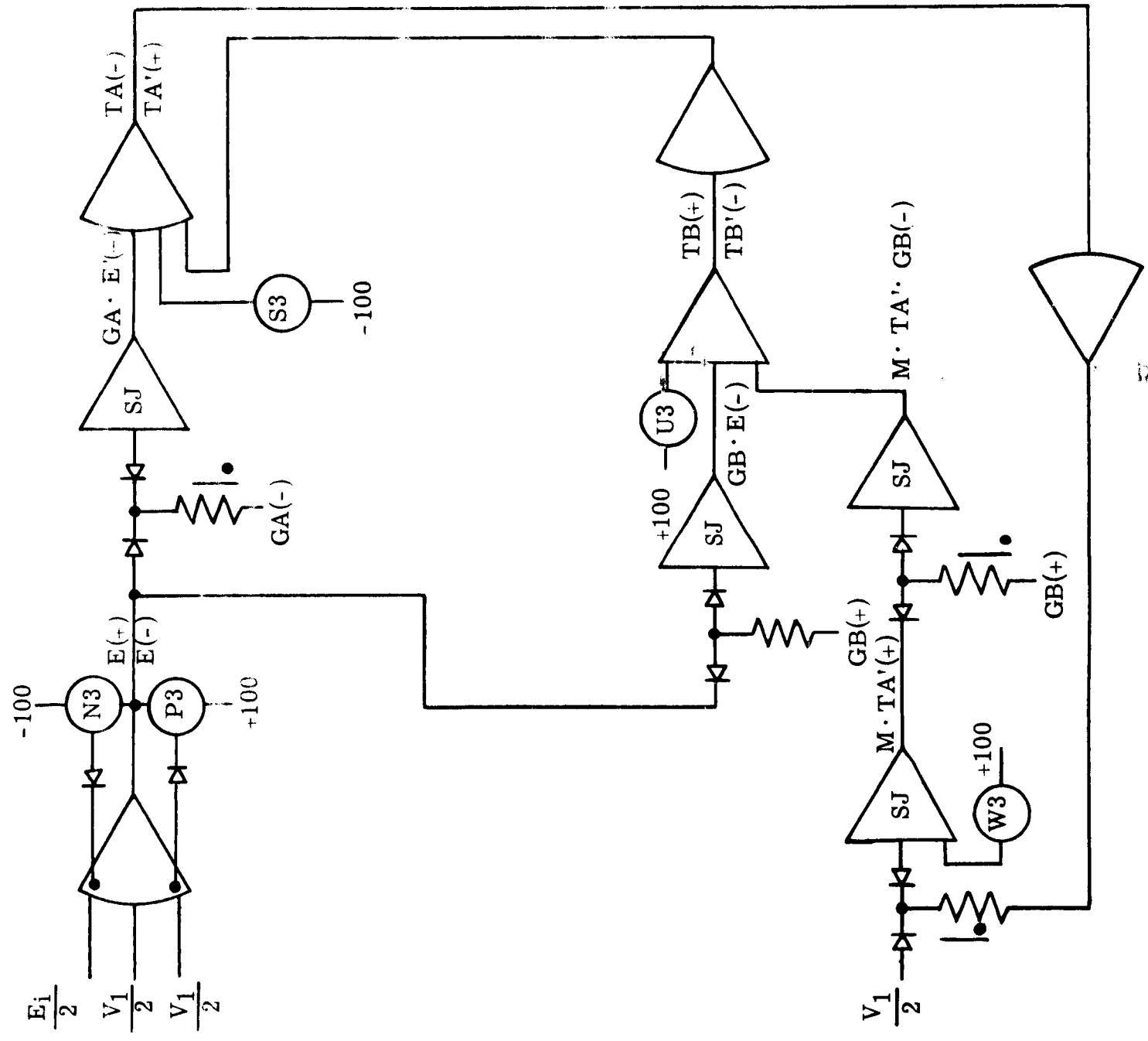


FIGURE 38

Logic For Thyatrons, Task B

DISTRIBUTION LIST

National Aeronautics & Space Administration
Scientific & Technical Information Facility
Box 5700
Bethesda 14, Maryland
Attn: NASA Representative (2 cys. + 1 repro.)

National Aeronautics & Space Administration
Lewis Research Center
21000 Brookpark Road
Cleveland, Ohio 44135

Attn: I. I. Pinkel, MS 5-3 (1)
Dr. L. Rosenblum, MS 106-1 (1)
R. L. Cummings, MS 500-201 (1)
H. A. Shumaker, MS 500-201 (1)
E. A. Koutnik, MS 500-201 (18)
B. Lubarsky, MS 500-201 (1)
C. S. Corcoran, MS 500-201 (1)
R. N. Shattuck, MS 21-5 (2)
W. L. Tiefferman, MS 77-1 (1)
R. L. Mather, MS 500-309 (1)
John E. Dilley, MS 500-309 (1)
Library, MS 3-7 (3)
Norman Musial-Patent Counsel Office,
MS 77-1 (1)
Report Control, MS 5-5 (1)
J. J. Weber, MS 3-16 (1)

National Aeronautics & Space Administration
Electronic Research Center
Power Conditioning & Distribution Laboratory
575 Technology Lane
Cambridge, Massachusetts 02139

National Aeronautics & Space Administration
Marshall Space Flight Center
Huntsville, Alabama
Attn: Russell H. Shelton
Ernst Stuhlinger

National Aeronautics & Space Administration
1520 H Street, N.W.
Washington 25, D. C.
Attn: James J. Lynch
Herbert Rothen

Naval Research Laboratory, Code 1572
Washington 25, D. C.
Attn: Mrs. Katherine H. Cass

North American Aviation, Incorporated
Los Angeles 45, California
Attn: Advanced Electrical Project

Oak Ridge National Laboratory
Oak Ridge, Tennessee
Attn: W. D. Manly

Office of Naval Research
Department of the Navy, Code 735
Washington 25, D. C.
Attn: E. E. Sullivan
For: Code 429

Pratt & Whitney Aircraft
East Hartford, Connecticut
Attn: William Lueckel

Commander, AFBMD
Headquarters, USAF ARDL
P. O. Box 262
Inglewood, California
Attn: Major George Austin

U. S. Atomic Energy Commission
Technical Information Service Extension
P. O. Box 62
Oak Ridge, Tennessee (3 copies)

U.S. Naval Ordnance Laboratory
White Oak, Silver Spring, Maryland
Attn: Eva Lieberman, Librarian

Westinghouse Electric Corporation
Aerospace Electric Division
Lima, Ohio
Attn: Library

Westinghouse Electric Corporation
Astronuclear Laboratory
P. O. Box 10864
Pittsburgh 36, Pennsylvania
Attn: D. Foster

Aeronautical Systems Division
(ASRMFP-3)
Wright-Patterson Air Force Base, Ohio
Attn: Lester Schott (2 cys.)

Advanced Research Project Agency
The Pentagon
Washington, D. C.
Attn: John Huth

Air Force Institute of Technology
Wright-Patterson Air Force Base, Ohio
Attn: Commandant

Air Technical Intelligence Center
Wright-Patterson Air Force Base, Ohio
Attn: Commander

Air University Library
Maxwell Air Force Base, Alabama
Attn: Director

AiResearch Manufacturing Company
Sky Harbor Airport
402 South 35th Street
Phoenix, Arizona
Attn: John Dannan

Commander, ARDC
Andrews Air Force Base
Washington 25, D. C.
Attn: RDTAPS, Capt. W. G. Alexander

U. S. Atomic Energy Commission
Germantown, Maryland
Attn: Lt. Col. G. M. Anderson
Col. Douthet
Herbert Rothen

AVCO
Wilmington, Massachusetts
Attn: Library

Chief, Bureau of Aeronautics
Washington 25, D. C.
Attn: C. L. Gerhardt, NP

Convair-Astronautics
5001 Kearny Villa Road
San Diego 11, California
Attn: Krafft A. Ehrlicke

USAF
Physical Electronics Branch
Wright-Patterson Air Force Base
W-P AFB, Ohio
Attn: Mr. Cartmell (AVTT)

General Electric Company
Missile & Space Vehicle Department
3198 Chestnut Street
Philadelphia 4, Pennsylvania
Attn: Edward Ray

Institute for Defense Analysis
Universal Building
1825 Connecticut Avenue, N.W.
Washington, D. C.
Attn: N. W. Snyder

Lockheed Missile & Space Division
Sunnyvale, California
Attn: Charles Burrell

Lockheed Missiles & Space Division
Building 526, Department 65-33
Sunnyvale, California
Attn: John N. Cox, Staff Engineer

National Aeronautics & Space Adm.
Ames Research Center
Moffett Field, California
Attn: Library

National Aeronautics & Space Adm.
Goddard Space Flight Center
Greenbelt, Maryland
Attn: Milton Schach

National Aeronautics & Space Adm.
Jet Propulsion Laboratories
California Institute of Technology
4800 Oak Grove Drive
Pasadena, California
Attn: John Paulson (2 cys.)

National Aeronautics & Space Adm.
Langley Research Center
Langley Field, Virginia
Attn: Library

Pratt & Whitney Aircraft Division
Connecticut Operations CANEL
P. O. Box 611
Middletown, Connecticut 06458
Attn: Dr. Robert Strough
W. H. Pennington